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# Sewage Research

## STUDIES OF SEWAGE PURIFICATION

### X. CHANGES IN CHARACTERISTICS OF ACTIVATED SLUDGE INDUCED BY VARIATIONS IN APPLIED LOAD

By C. C. Ruchhoft and R. S. Smith

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In a number of earlier papers, by this laboratory and others (1, 2, 3), studies of oxidation characteristics of activated sludge have been reported. It was found that the activated sludge alone was oxidized at a rather uniform rate. As soon as sewage was added the rate of oxygen utilization was increased, because of the oxidation of the nutrients in the sewage, by the tremendous bacterial population in the sludge. It was shown (4, 5) that the oxygen requirement of the sludge alone and its capacity for increased oxidation when given food were important characteristics of activated sludge. A later paper (6) presents the results of a study in which the rate of total purification of sewage and its rate of oxidation were observed simultaneously. The proportion of the total purification that was accounted for by oxidation was determined. The difference between the quantities of the total carbonaceous Biochemical Oxygen Demand (L value) of the substrate that is oxidized and that is removed by activated sludge was referred to as the net adsorption and synthesis.

In this paper are presented the results of experiments in which a small activated sludge plant was operated with varying loads to determine, for purposes of plant control, the value of such criteria of sludge condition as rates of total purification and of oxidation. These data supplement our previous conclusions concerning the importance of the quantity of oxygen required and the capacity of sludge to oxidize substrate, as indices of sludge condition.

#### Experimental

In the first test the sewage load was increased periodically on a small experimental activated sludge plant by the procedure of systematically diminishing the aeration time. The plant was first stabilized by operation on a 12-hour fill-and-draw aeration period, and was then changed to a continuous flow basis with the aeration time periodically reduced at successive intervals to 7.9, 5.8, 4.5, 3.2 and 2.3 hours. The length of operation on each aeration interval is indicated in Fig. 1. After 42 days of operation a breakdown in the sewage flow occurred requiring the termination of the experiment.

During the experimental period, data of plant operation were collected daily. The analyses made included suspended solids and 5-day Biochemical Oxygen Demand (B.O.D.) of the influent sewage; temperature, hydrogen ion concentration (pH), settleable solids and suspended solids of the aeration tank mixed liquor; per cent ash of the sludge and 5-day B.O.D. of the effluent. From these analyses, the sludge index, the plant load and the percentage reduction of the 5-day B.O.D. by the treatment plant were calculated. The plant load is expressed as pounds of 5-day B.O.D. per day introduced by the sewage per pound of suspended solids in the aeration tank * mixed liquor.

In these experiments the plant load was computed by the formula

$$\text{Plant load} = \frac{\text{5-day B.O.D. (p.p.m.)} \times \text{sewage flow (liters) in 24 hours}}{\text{Mixed liquor suspended solids (p.p.m.)} \times \text{capacity of aeration tank (liters)}}$$

For example, for this experimental plant with an aeration tank capacity of 205 liters, on December 4, 1936, the sewage flow was 1,217 liters in 24 hours with a 5-day B.O.D. of 212 p.p.m. and the aeration tank mixed liquor suspended solids averaged 2,568 p.p.m. Therefore, the plant load =

$$\frac{212 \times 1{,}217}{2{,}568 \times 205} = .490$$

All of the above operation data are presented in Table I and are plotted in Figs. 1 and 2. Figure 1 shows that there was very little change in the pH of the sewage or of the aeration mixture during this period. The temperature of the aeration mixture slowly decreased during the experiment from between 10 to 12° C. at the beginning to between 6 to 8° C. at the end. The suspended solids in the aeration mixture were maintained at between 2,100 and about 2,700 p.p.m. throughout the experimental run.

The percentage by weight of ash in the sludge decreased from around 30 per cent at the start of the experiment until a minimum value of about 18.5 per cent was reached on the twenty-sixth day after the plant had been operating on a 3.2 hour period for several days. From this point on the ash content fluctuated considerably, and the minimum value of 16.3 per cent for the entire experiment was obtained on the forty-first day.

At the beginning of the experiment the settling quality of the sludge was poor, but it improved slowly until the sludge index reached 19.3 at the same time that the minimum value of 18.5 per cent ash was obtained. These results are contrary to the general rule that the sludge index (calculated as the ratio of suspended solids in p.p.m. to the volume in ml. to which one liter of sludge settles in 30 minutes) is directly pro-

* It was realized that the solids in the entire system should be included in load calculations. However, measurements indicated that the quantities of suspended solids in the final settling tank were a minor factor (less than 5 per cent); consequently, for simplicity, aeration tank solids only were used in these load computations.

TABLE I.—*Plant Operation Data—Experiment 1*

| Date: 1936 | Influent Sewage | | | Activated Sludge Aeration Mixture | | | | | | Plant Effluent 5-day B.O.D. | Plant Loading Lbs. 5-day B.O.D. per Day per Lb. Susp. Solids in Aer. Mixture | Per Cent Reduction in 5-day B.O.D. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | pH | 5-day B.O.D. P.P.M. | Suspended Solids P.P.M. | Temp. ° C. | pH | Settleable Solids in 30 min. c.c./liter | Suspended Solids P.P.M. | Per Cent Ash in Sludge | Sludge Index | | | |
| Nov. 6 | 7.6 | 133 | 88 | 10.3 | 7.3 | 560 | 2284 | 28.7 | 4.1 | 7.2 | .140 | 94.6 |
| 7 | 7.4 | 83 | 82 | 12.3 | 7.2 | 705 | 2408 | 31.5 | 3.4 | 4.0 | .083 | 95.2 |
| 8 | 7.4 | 83 | 82 | 12.0 | 7.2 | 765 | 2408 | 31.5 | 3.2 | 4.0 | .083 | 95.2 |
| 9 | 7.5 | 190 | 160 | 12.3 | 6.9 | 758 | 2216 | 28.0 | 2.9 | 7.5 | .206 | 96.0 |
| 10 | 7.3 | 114 | 94 | 12.2 | 7.0 | 786 | 2696 | 29.4 | 3.4 | 5.8 | .139 | 94.9 |
| 11 | 7.7 | 225 | 121 | 11.5 | 7.1 | 758 | 2166 | 27.6 | 2.9 | 7.9 | .340 | 96.5 |
| 12 | 7.4 | 152 | 120 | 12.5 | 7.0 | 670 | 2232 | 22.9 | 3.3 | 10.3 | .223 | 93.2 |
| 13 | 7.3 | 165 | 106 | 12.5 | 7.0 | 503 | 2184 | 23.6 | 4.3 | 17.0* | .247 | 87.9† |
| 14 | 7.3 | 141 | 100 | 12.0 | 7.1 | 608 | 2472 | 25.9 | 4.1 | 3.1 | .187 | 97.8 |
| 15 | 7.3 | 141 | 100 | 11.0 | 7.1 | 573 | 2472 | 25.9 | 4.3 | 3.1 | .187 | 97.8 |
| 16 | 7.3 | 149 | 120 | 10.3 | 7.0 | 477 | 2464 | 26.1 | 5.2 | 10.2 | .198 | 93.1 |
| 17 | 7.4 | 155 | 119 | 11.0 | 7.0 | 303 | 2112 | 23.5 | 7.0 | 4.8 | .318 | 96.9 |
| 18 | 7.4 | 183 | 108 | 12.2 | 7.1 | 200 | 2136 | 21.0 | 10.6 | 6.7 | .282 | 96.3 |
| 19 | 7.5 | 256 | 108 | 9.0 | 7.2 | 245 | 2412 | 21.4 | 9.8 | 17.1* | .348 | 92.2† |
| 20 | 7.4 | 174 | 118 | 11.3 | 7.1 | 273 | 2688 | 22.6 | 9.9 | 4.4 | .276 | 91.3 |
| 21 | 7.5 | 268 | 104 | 11.3 | 7.1 | 247 | 2640 | 20.3 | 10.7 | 6.9 | .440 | 97.4 |
| 22 | 7.4 | 268 | 104 | 10.3 | 7.0 | 220 | 2640 | 20.3 | 12.0 | 6.9 | .440 | 97.4 |
| 23 | 7.5 | — | 167 | 9.5 | 7.1 | 217 | 2552 | 21.7 | 11.8 | — | — | — |
| 24 | 7.6 | 134 | 140 | 9.2 | 7.1 | 193 | 2544 | 21.5 | 13.2 | 14.2 | .228 | 89.4 |
| 25 | 8.2 | 185 | 134 | 8.8 | 7.2 | 162 | 2216 | 21.3 | 13.7 | 2.7 | .362 | 98.5 |
| 26 | 7.8 | 185 | 134 | 8.0 | 7.2 | 158 | 2216 | 21.3 | 14.0 | 2.7 | .362 | 98.5 |
| 27 | 7.8 | 160 | 124 | 7.0 | 7.2 | 155 | 2344 | 21.2 | 15.1 | 8.4 | .296 | 94.7 |
| 28 | 7.7 | 145 | 122 | 7.3 | 7.2 | 147 | 2240 | 21.8 | 15.2 | 4.5 | .280 | 96.9 |
| 29 | 7.6 | 145 | 122 | 8.0 | 7.0 | 143 | 2240 | 21.8 | 15.7 | 4.5 | .280 | 96.9 |
| 30 | 7.5 | 179 | 138 | 8.0 | 7.1 | 133 | 2240 | 21.1 | 16.8 | 14.3 | .473 | 92.0 |
| Dec. 1 | 7.6 | 190 | 120 | 7.2 | 7.1 | 128 | 2432 | 22.4 | 19.0 | 10.5 | .463 | 94.5 |
| 2 | 7.5 | 77 | 100 | 7.5 | 6.9 | 127 | 2452 | 18.5 | 19.3 | 7.7 | .186 | 90.0 |
| 3 | 8.0 | 169 | 100 | 8.7 | 7.1 | 130 | 2388 | 20.9 | 18.4 | 7.5 | .419 | 95.6 |
| 4 | 7.9 | 212 | 136 | 9.0 | 7.1 | 143 | 2568 | 19.0 | 18.0 | 8.7 | .490 | 95.9 |
| 5 | 7.7 | 119 | 92 | 7.0 | 7.1 | 163 | 2536 | 20.7 | 15.5 | 6.3 | .278 | 94.7 |
| 6 | 7.6 | 119 | 92 | 8.5 | 6.9 | 163 | 2536 | 20.7 | 15.5 | 6.3 | .278 | 94.7 |
| 7 | 8.0 | 237 | 106 | 7.7 | 7.1 | 163 | 2632 | 24.9 | 16.1 | 10.1 | .535 | 95.7 |
| 8 | 7.9 | 174 | 72 | 7.5 | 7.1 | 187 | 2236 | 25.2 | 11.9 | 10.5 | .463 | 94.0 |
| 9 | 7.8 | 139 | 73 | 7.8 | 7.1 | 203 | 2364 | 22.7 | 11.7 | 9.4 | — | 93.2 |
| 10 | 7.9 | 192 | 94 | 10.0 | 7.0 | 180 | 2176 | 24.1 | 12.1 | 11.0 | .523 | 94.3 |
| 11 | 7.8 | 185 | 96 | 7.7 | 7.1 | 220 | 2268 | 20.9 | 10.3 | 12.4 | .684 | 93.3 |
| 12 | 7.7 | 340 | 84 | 6.7 | 7.1 | 220 | 2012 | 23.7 | 9.2 | 6.1 | 1.420 | 98.4 |
| 13 | 7.7 | 340 | 84 | 6.5 | 7.1 | 228 | 2012 | 23.7 | 8.8 | 6.1 | 1.420 | 98.4 |
| 14 | 7.8 | 294 | 118 | 7.7 | 7.1 | 247 | 2056 | 19.5 | 8.3 | 15.9* | .598 | 93.2† |
| 15 | 7.6 | 133 | 137 | 8.3 | 7.0 | 287 | 2360 | 22.7 | 8.2 | 13.8 | .475 | 89.6 |
| 16 | 7.9 | 218 | 113 | 7.5 | 7.2 | 253 | 1960 | 18.6 | 7.8 | 10.4 | .934 | 95.2 |
| 17 | 7.7 | 259 | 115 | 7.5 | 7.3 | 263 | 2084 | 16.3 | 7.9 | 16.4* | 1.040 | 92.7† |
| 18 | 7.7 | 152 | 108 | 7.2 | 7.3 | 285 | 2232 | 20.6 | 7.8 | 15.3 | .572 | 90.0 |

* D.O. depleted after incubation in these samples consequently the B.O.D. values are low.
† These results are too high because effluent B.O.D. values are low.

portional to the percentage of ash in the sludge. As in this experiment an inverse relationship existed during the first 26 days, special conditions must have upset the general relationship between the percentage

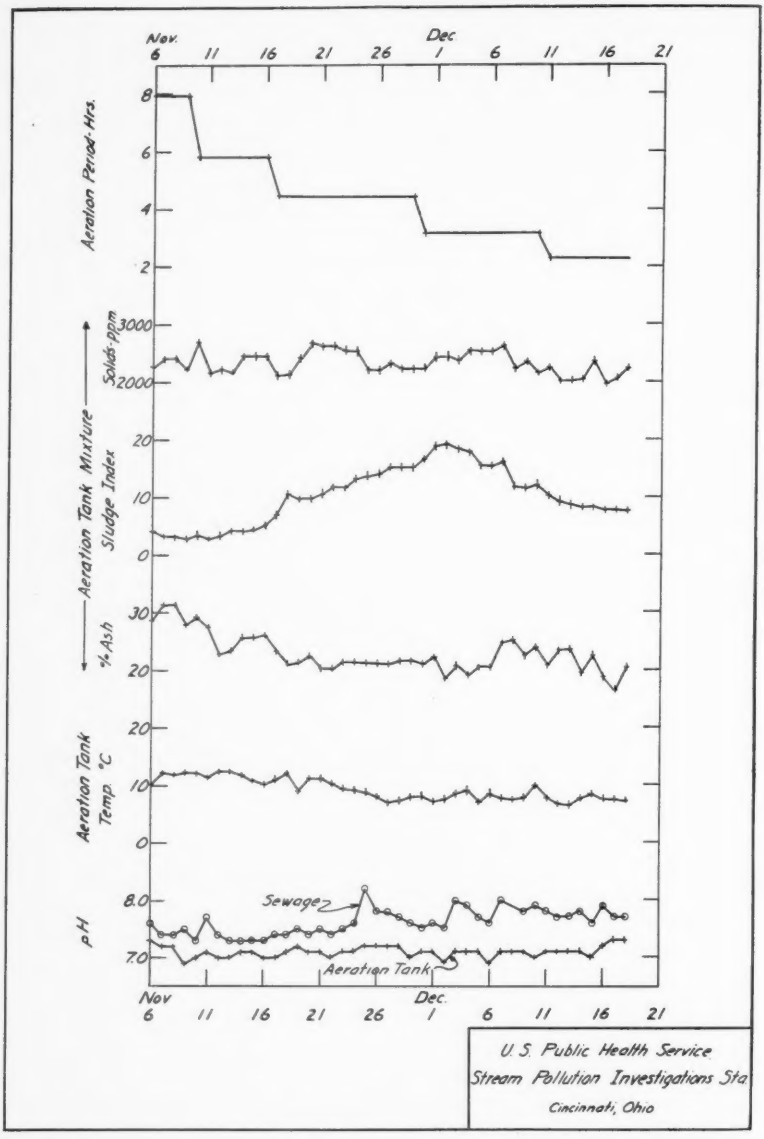


FIG. 1.—Plant operation data. Aeration period and aeration tank mixed liquor characteristics.

of ash in sludge and the sludge index. This unusual phenomenon has been noted before at this station.

Figure 2 shows that the suspended solids content of the sewage influent varied from about 85 to 165 p.p.m. during the experiment; also that the 5-day B.O.D. of this sewage fluctuated considerably from a minimum value of about 77 p.p.m. to a maximum of 340 p.p.m. The

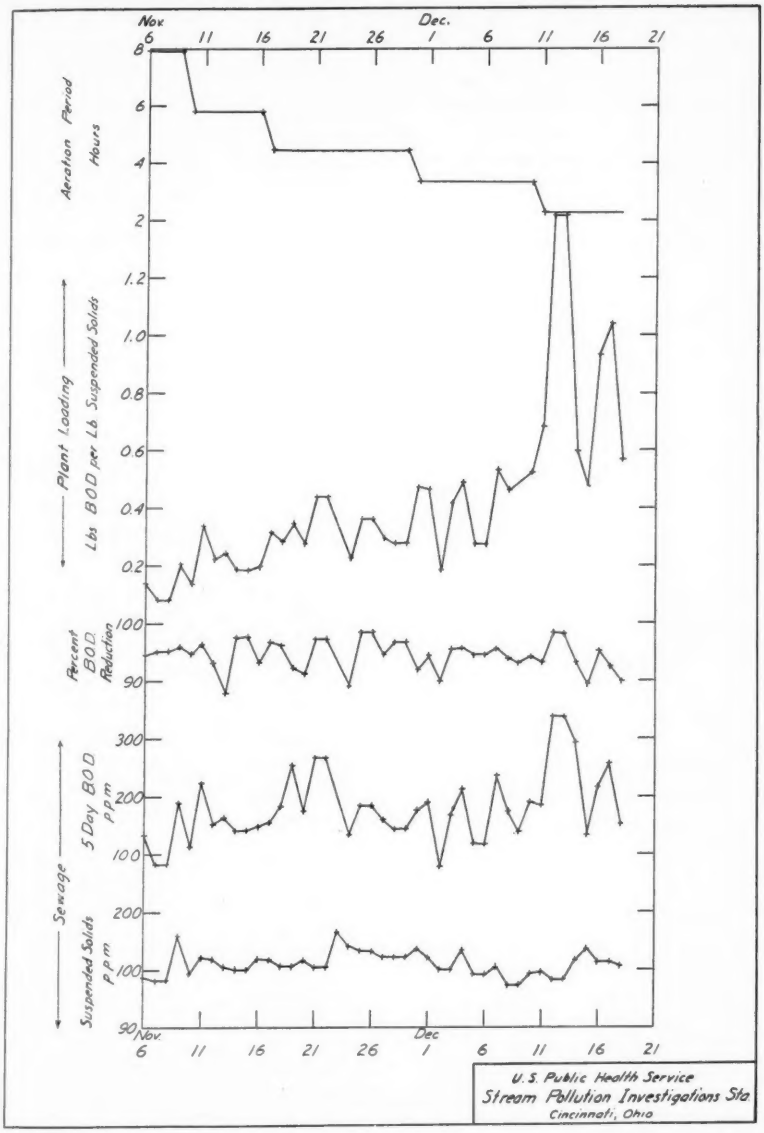


FIG. 2.—Plant operation data. Sewage strength, purification and plant loading.

plant loading, calculated in pounds of 5-day B.O.D. per pound of suspended solids in the aeration mixture, has been plotted in Fig. 2, which clearly shows the trend of increasing load during this experiment. The percentage of 5-day B.O.D. reduction obtained on the sewage passing through the plant varied between 88 and 98.5, but there was no regular decrease corresponding with increases in plant loading.

An examination of these operating data does not reveal the point at which overloading began. On the basis of sludge index it may appear that for a time the increased loading benefited the sludge. None of these common indices, however, gives any indication as to when the sludge reached an optimum biochemical condition from the standpoint of sewage purification or shows when the sludge was definitely overloaded.

TABLE II.—*Results of Substrate B.O.D. Removal Tests of Plant Sludge on Domestic Sewage*

*Experiment 1*

| Days after Start of Experiment | 0 | 3 | 7 | 10 | 14 | 17 | 20 | 23 | 27 | 31 | 34 | 38 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| **Dilution Method 5-day B.O.D. of Substrates (P.P.M.)** | | | | | | | | | | | | |
| Old Supernatant | 6.2 | 15.5 | 17.6 | 13.3 | 29.3 | 18.7 | 16.3 | 21.2 | 12.6 | 16.6 | 32.7 | 24.2 |
| Sewage Feed | 202.0 | 189.0 | 249.0 | 234.0 | 224.0 | 213.0 | 229.0 | 220.0 | 256.0 | 222.0 | 316.0 | 104.0 |
| Initial Supernatant Substrate* | 123.7 | 119.6 | 156.4 | 145.7 | 146.1 | 135.3 | 143.9 | 140.5 | 158.6 | 139.8 | 202.7 | 72.1 |
| Supernatant Substrate After: | | | | | | | | | | | | |
| 1½ hrs. aeration | 25.3 | 24.9 | 17.8 | 19.6 | 21.6 | 33.7 | 22.3 | 31.7 | 34.7 | 35.3 | 48.7 | 28.7 |
| 3 hrs. aeration | 17.2 | 16.0 | 13.5 | 13.4 | 15.8 | 19.4 | 14.0 | 19.2 | 25.4 | 37.8 | 21.7 | 22.7 |
| 5 hrs. aeration | 12.4 | 10.7 | 11.3 | 9.9 | 17.3 | 19.0 | 15.4 | 21.2 | 24.1 | 25.7 | 27.5 | 19.2 |
| **Dilution Method 20-day B.O.D. of Substrates (P.P.M.)** | | | | | | | | | | | | |
| Old Supernatant | 13.0 | 24.1 | 47.9 | 26.9 | 44.6 | 43.4 | 56.1 | 61.1 | 68.8 | 67.3 | 83.2 | 85.5 |
| Sewage Feed | 365.0 | 524.0 | 455.0 | 388.0 | 455.0 | 426.0 | 549.0 | 457.0 | 666.0 | 656.0 | 756.0 | 353.0 |
| Initial Supernatant Substrate* | 224.2 | 324.0 | 292.2 | 243.6 | 290.8 | 273.0 | 351.8 | 298.6 | 427.1 | 420.5 | 486.9 | 246.0 |
| Supernatant Substrate After: | | | | | | | | | | | | |
| 1½ hrs. aeration | 126.6 | 114.1 | 116.8 | 74.6 | 101.5 | 141.9 | 138.4 | 159.9 | 227.2 | 231.2 | 292.0 | 149.1 |
| 3 hrs. aeration | 112.2 | 88.7 | 75.2 | 74.9 | 68.7 | 75.3 | 116.0 | 128.7 | 185.0 | 177.0 | 190.0 | 150.2 |
| 5 hrs. aeration | 73.5 | 81.2 | 41.5 | 19.5 | 30.6 | 62.0 | 62.2 | 92.8 | 82.6 | 167.7 | 166.2 | 157.2 |
| **Percentage Reduction of 20-day B.O.D. Substrate** | | | | | | | | | | | | |
| After 1½ hrs. aeration | 43.5 | 64.8 | 60.0 | 69.4 | 65.1 | 48.0 | 60.7 | 46.5 | 46.8 | 45.0 | 40.0 | 39.4 |
| 3 hrs. aeration | 50.0 | 72.6 | 74.3 | 69.3 | 76.4 | 72.4 | 67.0 | 56.9 | 56.7 | 57.9 | 61.0 | 38.9 |
| 5 hrs. aeration | 67.2 | 74.9 | 85.8 | 92.0 | 89.5 | 77.3 | 82.3 | 68.9 | 80.7 | 60.1 | 65.9 | 36.1 |

* Each value represents the quantity of oxygen required by .6 liter of sewage plus .4 liter of old supernatant.

An evaluation of the changes taking place in the biochemical quality of the sludge during this loading experiment was attempted by means of the sludge and substrate-feed mixture oxidation tests and 20-day substrate B.O.D. removal test. Eight liter samples of sludge were taken from the plant periodically for this purpose and the tests were made as described (5, 6) previously. Twelve series of these tests were run upon sludge removed from the plant during this experiment.

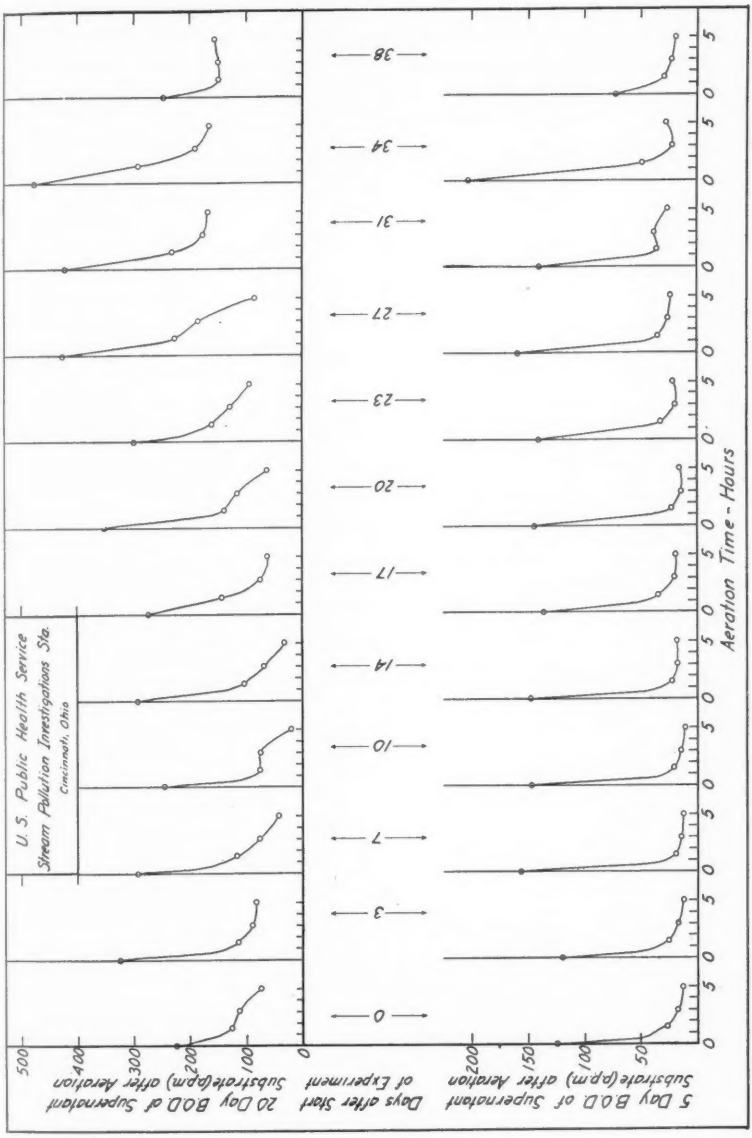


FIG. 3.—Efficiency of sludge as measured by decrease in B.O.D. of supernatant substrate during aeration in a closed system.

The substrate B.O.D. removal tests were made by adding the sewage feed to the settled solids from a 6 liter sample of the aeration mixture from the tank. The sewage and the sludge were brought to 20° C. and, after mixing, were aerated at this temperature in the laboratory for five hours. The 5-day and 20-day B.O.D. were determined on the old supernatant removed when the aeration mixture was taken and on the sewage

TABLE III.—*Results of Oxidation Tests with Plant Sludge on Domestic Sewage*

*Experiment 1*

| Days after Start of Experiment.. | 0 | 3 | 7 | 10 | 14 | 17 | 20 | 23 | 27 | 31 | 34 | 38 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test No..... | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Suspended Solids in Sludge, P.P.M..... | 2372 | 2460 | 2252 | 2576 | 2596 | 2336 | 2360 | 2140 | 2392 | 2444 | 2080 | 3364 |
| Mgms. Oxygen Used by Control Mixture (*B*) | | | | | | | | | | | | |
| 1½ hrs. aeration... | 15.0 | 18.6 | 27.4 | 21.0 | 35.0 | 23.2 | 29.2 | 27.5 | 51.6 | 37.8 | 38.5 | 55.0 |
| 3 hrs. aeration.... | 27.1 | 32.4 | 50.2 | 42.2 | 62.1 | 40.1 | 57.5 | 59.8 | 101.2 | 75.5 | 71.5 | 117.8 |
| 5 hrs. aeration.... | 36.6 | 48.4 | 78.9 | 50.8 | 100.7 | 68.7 | 98.4 | 98.8 | 150.2 | 105.9 | 109.9 | 165.0 |
| Mgms. Oxygen Used by Food Aeration Mixture (*A*) | | | | | | | | | | | | |
| 1½ hrs. aeration... | — | 51.1 | 56.6 | 62.8 | 57.4 | 47.5 | 57.1 | 59.5 | 70.5 | 47.8 | 69.5 | 64.9 |
| 3 hrs. aeration.... | 75.5 | 83.2 | 98.7 | 98.0 | 94.8 | 87.0 | 100.7 | 103.0 | 133.7 | 92.3 | 115.8 | 118.6 |
| 5 hrs. aeration.... | 89.1 | 116.9 | 136.2 | 143.4 | 141.4 | 131.0 | 165.9 | 156.6 | 203.9 | 133.8 | 158.3 | 156.5 |
| *C* = Mgms. Oxygen Used to Oxidize Substrate Feed (*A*–*B*) | | | | | | | | | | | | |
| 1½ hrs. aeration... | — | 32.5 | 29.2 | 41.8 | 22.4 | 24.3 | 27.9 | 32.0 | 18.9 | 10.0 | 31.0 | 9.9 |
| 3 hrs. aeration.... | 48.4 | 50.8 | 48.5 | 55.8 | 32.7 | 46.9 | 43.2 | 43.2 | 32.5 | 16.8 | 44.3 | 0.8 |
| 5 hrs. aeration.... | 52.5 | 68.5 | 57.3 | 92.6 | 40.7 | 62.3 | 67.5 | 57.8 | 53.7 | 27.9 | 48.4 | −8.5 |
| *D* = Percentage of 20-day Substrate Feed B.O.D. Oxidized* | | | | | | | | | | | | |
| 1½ hrs. aeration... | — | 10.3 | 10.7 | 18.0 | 8.2 | 9.5 | 8.5 | 11.7 | 4.7 | 2.5 | 6.8 | 4.7 |
| 3 hrs. aeration.... | 22.1 | 16.2 | 17.8 | 24.0 | 12.0 | 18.3 | 13.1 | 15.8 | 8.1 | 4.3 | 9.8 | 0.38 |
| 5 hrs. aeration.... | 24.0 | 21.8 | 21.0 | 39.8 | 14.9 | 24.4 | 20.5 | 21.1 | 13.4 | 7.1 | 10.7 | −4.0 |
| *E* = Mgms. Oxygen Per Gram Suspended Solids in Control Mixture | | | | | | | | | | | | |
| 1½ hrs. aeration... | 6.3 | 7.6 | 12.2 | 8.2 | 13.5 | 9.9 | 12.4 | 12.9 | 21.6 | 15.5 | 18.5 | 16.3 |
| 3 hrs. aeration.... | 11.4 | 13.2 | 22.3 | 16.4 | 23.9 | 17.2 | 24.4 | 27.9 | 42.3 | 30.9 | 34.4 | 35.0 |
| 5 hrs. aeration.... | 15.4 | 19.7 | 35.0 | 19.7 | 38.8 | 29.4 | 41.7 | 46.2 | 62.8 | 43.3 | 52.8 | 49.0 |

* This is obtained by dividing the *C* values by 0.6 of the 20-day sewage food values in p.p.m. as given on Table II and multiplying by 100. (There were 600 ml. of sewage used as feed.)

feed added. These values for all tests are given in Table II. The initial B.O.D. of the mixed substrate was calculated from the B.O.D. of the old supernatant and that of the sewage added as given in Table II. After one and one-half, three and five hours, supernatant was removed from the aeration mixture in the test bottle and the 5-day and 20-day B.O.D. determined. From the values of B.O.D. remaining in the supernatant after these aeration periods and the initial B.O.D. of the sub-

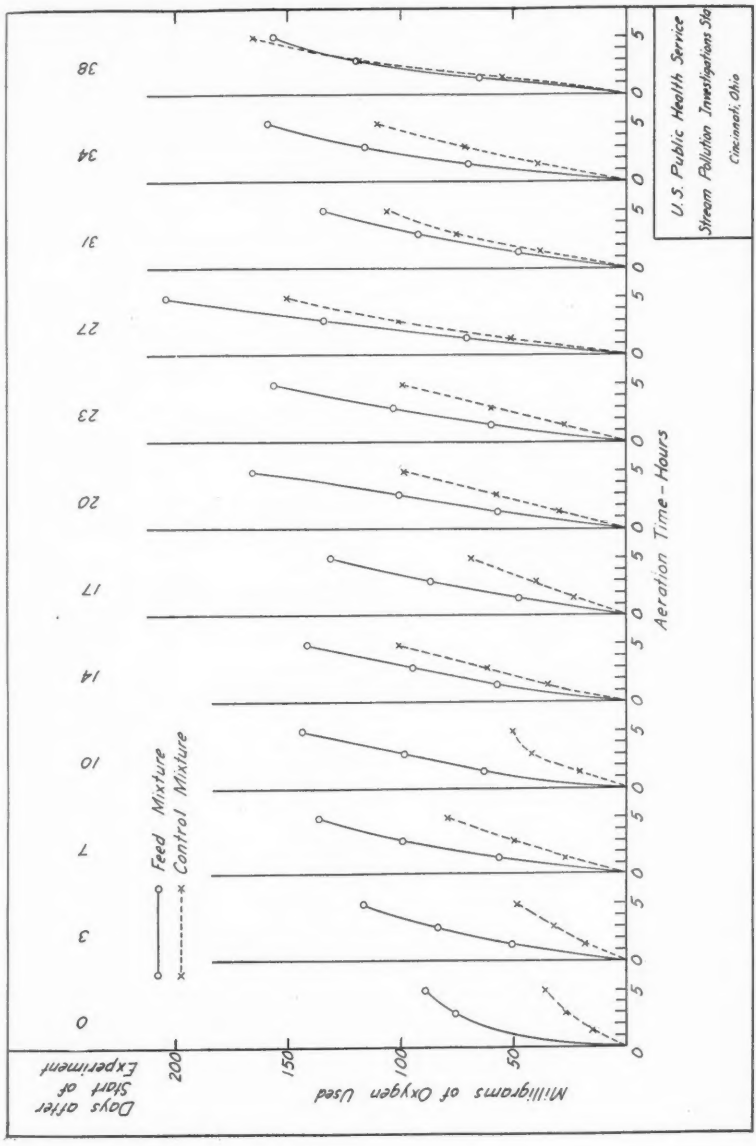


FIG. 4.—Oxygen utilization of control sludge and sludge with added sewage measured while undergoing aeration in a closed system.

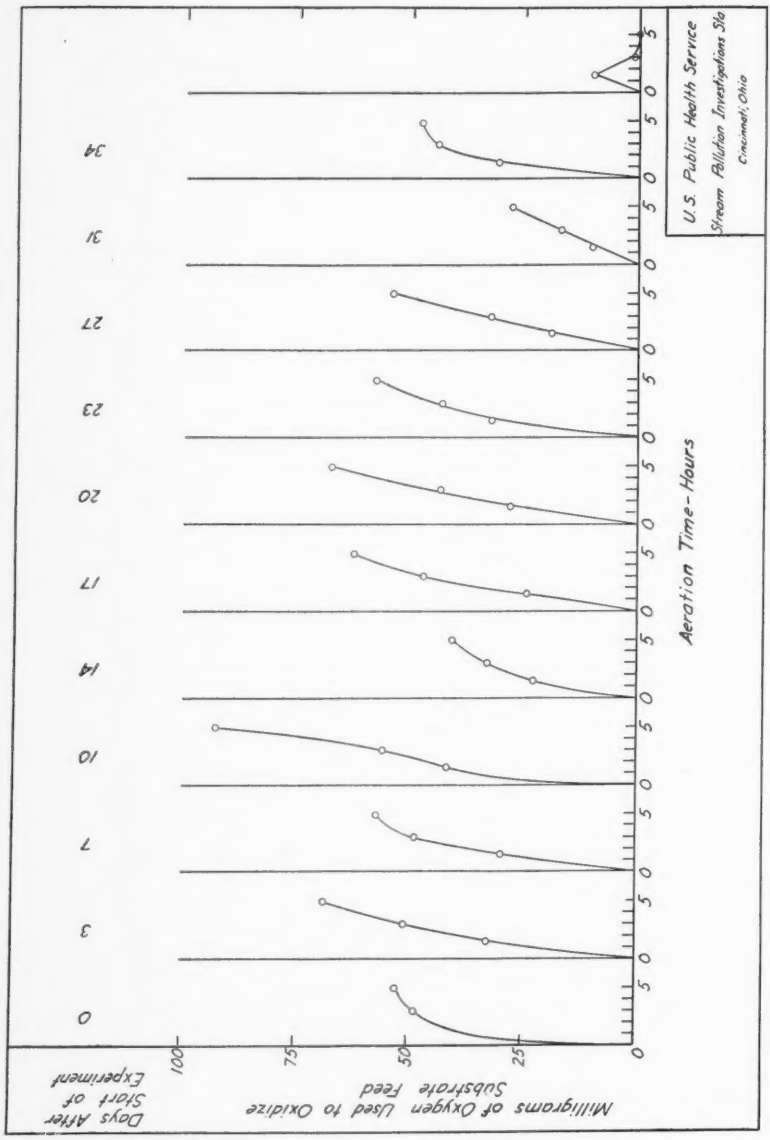
Days After Start of Experiment
Milligroms of Oxygen Used to Oxidize Substrate Feed
Aeration Time-Hours
U.S. Public Health Service
Stream Pollution Investigations Sta
Cincinnati, Ohio

FIG. 5.—Oxidation of substrate feed by activated sludge as measured by the differences in oxygen utilization of control sludge and sludge with added sewage in closed aeration systems.

strate, the percentage of the 20-day substrate B.O.D. that was removed was calculated and is also given in Table II.

The substrate B.O.D. removal performance of the sludge obtained during these tests is shown in a series of curves in Fig. 3. During the first four tests, representing the first 10-day operation period, the 5-day substrate B.O.D. removal test showed no change in the sludge. The next four tests showed a slightly lowered efficiency in the 5-day substrate removal performance. In the last four tests the five day substrate B.O.D. removal capacity of the sludge became further impaired. However, at no time during these tests was a striking change indicated in the 5-day B.O.D. removal performance of the sludge in spite of increasing loads put on the plant. This probably may be interpreted as

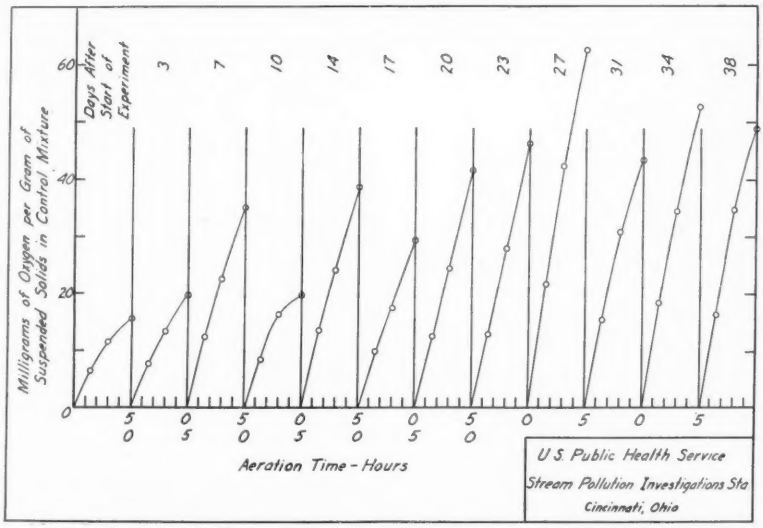


FIG. 6.—Oxygen requirement per gram of suspended solids in the control sludge.

indicating that the 5-day B.O.D. removal test on sludge is a rather poor and insensitive indicator of the biochemical condition of the sludge.

An examination of the results obtained in the 20-day substrate B.O.D removal tests, which are also plotted in Fig. 3, indicates that this test is a better indicator of change in sludge condition than the 5-day B.O.D. removal test. However, because of the long incubation time required, it has no practical value in plant operation.

The data for the oxidation tests performed during this experiment are given in Table III. The data for the oxygen required for the sludge control and for the sludge plus feed mixture are plotted in Fig. 4. These curves show that the oxygen requirement and the rate of oxygen utilization of the control sludge during the first 3-hour aeration period increased tremendously as this experiment progressed. While there was some increase in the rate of oxygen utilization of the sludge-feed

mixture in the tests until the twenty-seventh day of the experiment, this did not keep up with the increasing rate in the control sludge. Consequently, the difference in the quantities of oxygen utilized by these systems, which difference represents substantially the oxidation of the substrate, declined after the tenth day of the experiment. This will be observed in Fig. 5 where the oxygen results obtained, as described for substrate oxidation, are plotted. An examination of Figs. 4 and 5 indicates that the biochemical qualities of the sludge were not injured and may have been benefited somewhat by increased load until the tenth day of the experiment. A decided decrease in the substrate oxidation capacity is indicated by the fifth test on the fourteenth day and, although some recovery is indicated in the following two tests, there was,

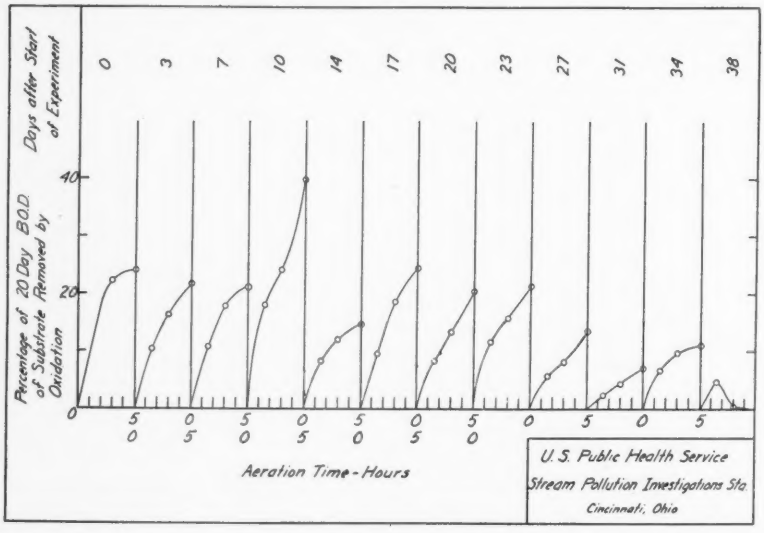


FIG. 7.—Percentage of 20-day B.O.D. of sewage feed oxidized by activated sludge.

with one exception, a consistent decrease in the oxidation capacity of the sludge thereafter. On the final test, the sludge control required as much oxygen during the 3 and 5-hour aeration period as the sludge feed mixture, a condition which indicated a badly overloaded sludge.

Figure 6 shows the oxygen requirement per gram of control sludge during this experiment. This parameter shows that there was a general increase in the oxygen requirement per gram of control sludge during the one and one-half and three hour aeration periods after the tenth day of the experiment. On the basis of these data it may be concluded that if the control sludge oxygen requirement per gram exceeds about 12 mgm. in one and one-half hours or 25 mgm. in three hours, the danger point for the continued successful operation of the system is being approached. This indicator of activated sludge condition is easily obtained and seems to be an excellent one for practical

application in plant control. The curves in Fig. 7 show the percentage of the 20-day B.O.D. of the substrate that is oxidized by the activated sludge in this experiment. They indicate very strikingly the decreasing efficiency of the sludge for oxidizing substrate during the course of this test.

## Experiment on Long Reaeration of Sludge

The purpose of the second experiment was to study changes in the oxidizing powers of activated sludge during a prolonged aeration period without feeding. In this experiment the experimental activated

Table IV.—*Base Data and Results of B.O.D. Removal Tests of Plant Sludge on Domestic Sewage Experiment 2*

(Activated Sludge Aeration Without Feeding)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Date: 1936, Oct. | 5 | 6 | 7 | 8 | 9 | 12 | 15 | 19 |
| Aeration Period Hrs. | 8 | Inf. | Inf. | Inf. | Inf. | Inf. | Inf. | Inf. |
| Days after Last Feeding | — | 0 | 1 | 2 | 3 | 6 | 9 | 13 |
| Susp. Solids, P.P.M. | 2808 | 2672 | 2464 | 2168 | 2208 | 2204 | 2164 | 1868 |
| Sludge Index | 29.8 | 29.8 | 29.0 | 27.1 | 27.6 | 24.4 | 24.0 | 19.6 |
| Per Cent Ash in Sludge | 24.1 | 23.1 | 24.9 | 23.9 | 25.0 | 27.6 | 31.4 | 30.0 |
| Dilution Method—20 day B.O.D. (P.P.M.) | | | | | | | | |
| Old Supernatant | 40.0 | 26.6 | 33.6 | 67.0 | 39.2 | 51.6 | 42.7 | 31.0 |
| Sewage Feed | 491.0 | 590.0 | 513.0 | 613.0 | 377.0 | 368.0 | 329.0 | 349.0 |
| Initial Supernatant Substrate* | 310.6 | 364.6 | 321.2 | 394.6 | 241.9 | 241.4 | 214.5 | 221.8 |
| Supernatant Substrate After: | | | | | | | | |
| 1½ hrs. aeration | 131.0 | 172.0 | 146.0 | 210.0 | 133.0 | 124.5 | 106.0 | 153.0 |
| 3 hrs. aeration | 78.7 | 95.7 | 99.5 | 136.0 | 114.0 | 86.7 | 94.6 | 146.0 |
| 5 hrs. aeration | — | 45.9 | 43.4 | 28.6 | 80.6 | 71.9 | 71.5 | 136.0 |
| Percentage Reduction of 20 day B.O.D. of Substrate | | | | | | | | |
| After 1½ hrs. aeration | 57.8 | 52.8 | 54.5 | 46.8 | 44.9 | 48.4 | 50.6 | 31.0 |
| After 3 hrs. aeration | 74.7 | 73.8 | 69.0 | 65.5 | 52.8 | 64.1 | 55.9 | 34.2 |
| After 5 hrs. aeration | — | 87.4 | 86.5 | 92.8 | 66.6 | 70.2 | 66.7 | 38.7 |

* Each value represents the quantity of oxygen required by .6 liter sewage plus .4 liter old supernatant.

sludge plant was operated on an 8-hour aeration period for eight days to obtain a good, normal activated sludge. During this preliminary period, four total purification and oxidation tests similar to those described for Experiment 1, were run to determine the characteristics of the sludge. Then the sewage feed was cut off, but the tank aeration mixture was aerated at the normal rate for a period of thirteen days. Periodically, during the aeration period, samples of sludge were removed and the tests already described were performed using domestic sewage as the feed. The results of these tests during this experiment have been summarized in Tables IV and V and some of the most significant data indicating change in sludge condition have been plotted in

Figs. 8, 9 and 10. The quantities of oxygen used during the 5-hour aeration period of these tests decreased regularly on both the control sludge (*B*) and the aeration mixture (*A*). However, the difference between (*A*) and (*B*) gradually became less, indicating again that the ability of the sludge to oxidize the added sewage substrate used in the test was being lost. This is best shown in Fig. 8 where the quantities of oxygen representing the oxidation of substrate (*A*–*B*) have been

TABLE V.—*Results of Oxidation Tests with Plant Sludge on Domestic Sewage Experiment 2*

(Activated Sludge Aeration Without Feeding)

| Days after Last Feeding... | — | 0 | 1 | 2 | 3 | 6 | 9 | 13 |
|---|---|---|---|---|---|---|---|---|
| Test Number | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Mgms. Oxygen Used by Control Mixture (*B*) | | | | | | | | |
| 1½ hrs. aeration | 35.1 | 27.3 | 12.9 | 17.3 | 19.7 | 18.3 | — | 10.3 |
| 3 hrs. aeration | 53.2 | 48.8 | 36.5 | 32.1 | 32.1 | 32.5 | 27.7 | 15.9 |
| 5 hrs. aeration | — | 71.1 | 59.4 | 50.6 | 45.0 | 45.8 | 43.1 | 22.7 |
| Mgms. Oxygen Used by Feed Aeration Mixture (*A*) | | | | | | | | |
| 1½ hrs. aeration | 83.4 | 77.8 | 59.2 | 58.9 | 55.4 | 23.5 | 16.3 | 14.7 |
| 3 hrs. aeration | 145.9 | 134.3 | 92.9 | 95.0 | 79.3 | 42.9 | 38.3 | 21.2 |
| 5 hrs. aeration | — | 175.1 | 126.5 | 120.4 | 107.5 | 69.6 | 61.3 | 23.6 |
| *C* = Mgms. Oxygen Used to Oxidize Substrate Feed (*A*–*B*) | | | | | | | | |
| 1½ hrs. aeration | 48.3 | 50.5 | 46.3 | 41.6 | 35.7 | 5.2 | — | 4.4 |
| 3 hrs. aeration | 92.7 | 85.5 | 56.4 | 62.9 | 47.2 | 10.4 | 10.6 | 5.3 |
| 5 hrs. aeration | — | 104.0 | 67.1 | 69.8 | 62.5 | 23.8 | 18.2 | 0.9 |
| *D* = Percentage of 20-day Substrate Feed B.O.D. Oxidized* | | | | | | | | |
| 1½ hrs. aeration | 16.4 | 14.3 | 15.0 | 11.3 | 15.8 | 2.4 | — | 2.1 |
| 3 hrs. aeration | 31.5 | 24.2 | 18.3 | 17.1 | 20.9 | 4.7 | 5.4 | 2.5 |
| 5 hrs. aeration | — | 29.4 | 21.8 | 19.0 | 27.6 | 10.8 | 9.2 | 0.4 |
| *E* = Mgms. Oxygen per Gram Suspended Solids in Control Mixture | | | | | | | | |
| 1½ hrs. aeration | 12.5 | 10.2 | 5.24 | 7.98 | 8.92 | 8.30 | — | 5.51 |
| 3 hrs. aeration | 18.9 | 18.3 | 14.8 | 14.8 | 14.5 | 14.7 | 12.8 | 8.51 |
| 5 hrs. aeration | — | 26.6 | 24.1 | 23.3 | 20.4 | 20.8 | 19.9 | 12.2 |

* This is obtained by dividing the *C* values by 0.6 of the 20-day sewage feed values in p.p.m. as given in Table IV and multiplied by 100. (There were 600 ml. of sewage used as feed.)

plotted for each test after the feed was stopped in the aeration tank. This indicates that starving a sludge, while decreasing the demand of the sludge itself, also decreases its ability to oxidize nutrient substrate feed which may be added to it. Once this oxidizing ability is lost by prolonged aeration it can be redeveloped only gradually as is done initially. In this case there was not a great deal of damage done during the first three days of aeration following elimination of the feed, but between the third and sixth days there was a very great loss in the ability of the sludge to oxidize sewage. By the ninth day this oxidizing

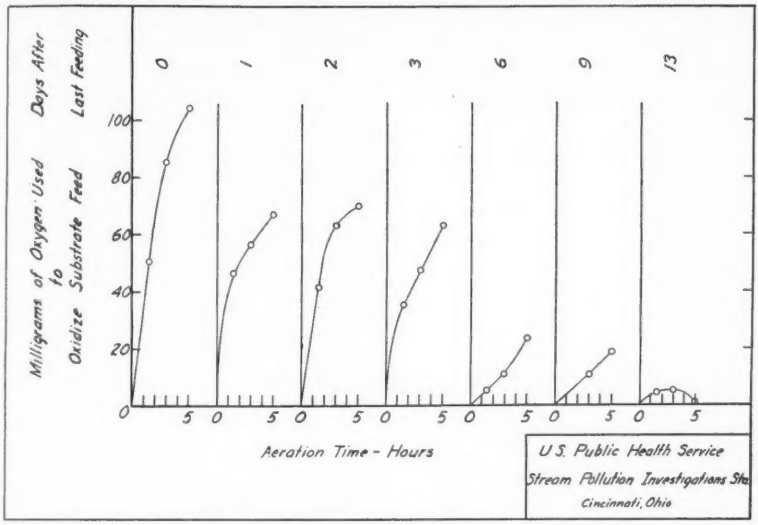


FIG. 8.—Oxidation of substrate feed by activated sludge in closed system as sludge deteriorated during long continued reaeration.

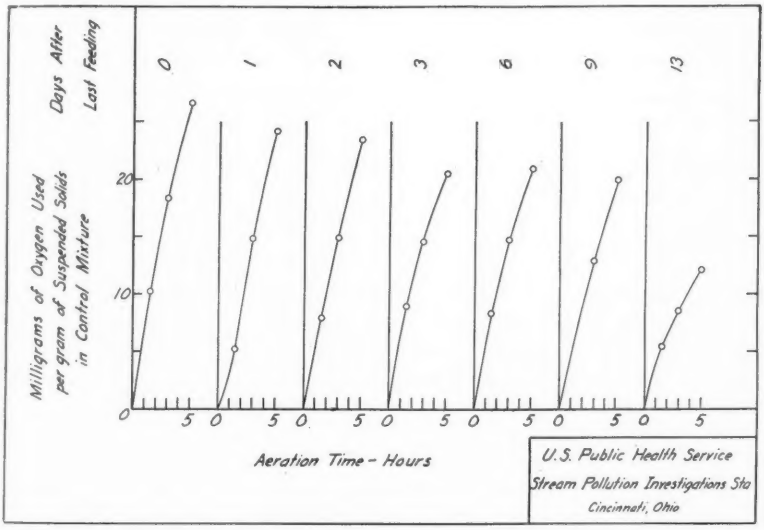


FIG. 9.—Oxygen requirement per gram of solids in the control sludge during long continued reaeration.

ability was very poor and had practically disappeared by the thirteenth day.

The quantities of oxygen used per gram by the control sludge in each test are plotted in Fig. 9. This series of curves shows that the rates and quantities of oxygen used by the sludge gradually decreased

in this experiment. This is, as would be expected, exactly the opposite result obtained in the overloading experiment.

The series of curves in Fig. 10 are similar to those in Fig. 7 for the first experiment and show the reduction, which was the result of

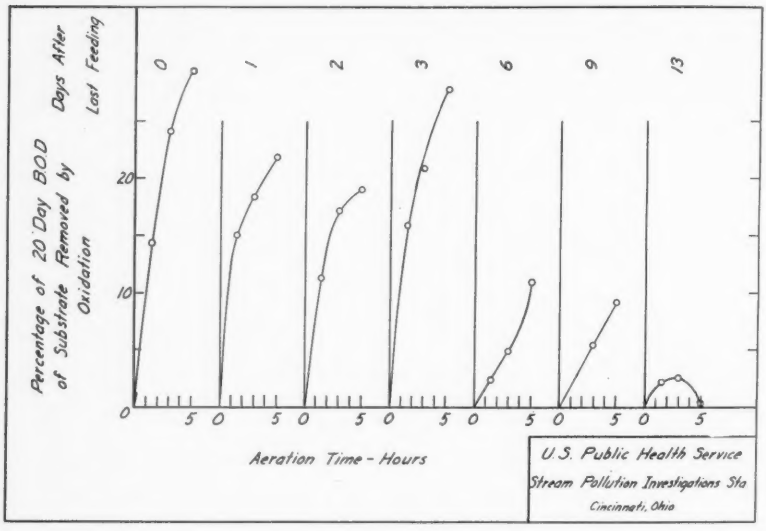


FIG. 10.—Percentage of 20-day B.O.D. of sewage feed oxidized by activated sludge following various periods of long reaeration.

starvation, in the percentages of the 20-day B.O.D. of the substrate removed by oxidation.

## SUMMARY

In an experiment on overloading of activated sludge and on another with starvation (prolonged aeration without food) suspended solids, sludge index, sludge ash, total B.O.D. removal tests, short time oxygen demands of sludge and substrate oxidation tests were used as parameters of change in sludge condition. The experiments indicated that while the sludge index and sludge ash were important criteria from the settling standpoint, they were very poor indices of change in biochemical quality of the sludge. The B.O.D. removal tests were also poor and insensitive indicators of change in biochemical qualities. The 20-day B.O.D. removal test was superior to the 5-day test as an indicator of past change, but was of no practical value in plant control because of the long incubation period involved.

The short time oxygen utilization tests on activated sludge appeared to be better indices of change than any of the above parameters. It was shown that the quantity of oxygen used per gram of suspended solids during a short aeration period of the mixed liquor sample undergoing test gradually increased with overloading of the sludge. With

cessation of sewage feed to the mixed liquor maintained under continuous aeration, this oxygen use was slowly reduced. Practical tests of this nature can be made easily and this procedure may prove to be a valuable aid in activated sludge plant control, particularly as an indicator of overloading.

These experiments indicate that the substrate oxidation tests are sensitive indicators of change of biochemical quality of activated sludge. It appears that this most important property of an activated sludge is gradually lost either by prolonged overloading or by starvation. Prolonged aeration without food (sludge reaeration) altered the normal characteristics of activated sludge to the point where the aerated sludge had entirely lost its ability to oxidize sewage substrate at high rates.

Acknowledgment is made to former Assistant Chemist P. D. McNamee for much of the analytical work on which this paper is based.

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# STUDIES ON THE METHANE-PRODUCING BACTERIA *

## I. DEVELOPMENT OF A METHOD FOR ENUMERATION

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### Introduction

In any bacteriological technique, which measures the number of organisms present in a medium, it is essential to develop a satisfactory method which takes due cognizance of the physiological properties of the organisms to be enumerated. The information available on the methane-producing organisms is very meager. They possess characteristics which make them exceedingly difficult to study by the ordinary routine bacteriological techniques. Although they have never been isolated in pure culture certain facts are known. According to Barker [1] the organisms are strict anaerobes which do not form spores; in addition to a hydrogen donator (usually an organic compound) they require carbon dioxide as a hydrogen-acceptor; they require only inorganic nitrogen sources; and they grow slowly.

Barker [1] presented a survey of the methane-producing organisms based on the descriptions which were scattered throughout the literature. He developed methods for obtaining highly purified cultures of four different types of methane-producing organisms which allowed positive identifications on the basis of morphological and physiological characteristics, and described them as follows:

1. *Methanosarcina methanica.* Large spherical cells characteristically grouped to form cubical sarcina packets. Permanently immotile and nonspore-forming. Ferments acetic and butyric acids with the production of methane, but not ethyl or butyl alcohol. Gram variable.
2. *Methanococcus Mazei n. sp.* Small spherical cells which occur singly, in small groups, or in large, irregular and somewhat slimy aggregates. Immotile and nonspore-forming. Ferments acetic and butyric acids with the production of methane, but not ethyl or butyl alcohols. Gram variable.
3. *Methanobacterium Söhngenii n. sp.* Rod-shaped, permanently immotile, nonspore-forming cells. The rods are characteristically joined into long threads which lie parallel to one another so as to form bundles. Ferments acetic and butyric acids with the production of methane, but not ethyl alcohol. Gram negative.
4. *Methanobacterium Omerlianskii n. sp.* Thin, frequently bent, immotile, nonspore-forming rods. Ferments ethyl alcohol to acetic

* Journal Series Paper, N. J. Agricultural Experiment Station, New Brunswick, N. J., Dept. Water and Sewage Research.

acid and butyl alcohol to butyric acid with methane formation. The same organism probably also ferments butyric acid to acetic acid. Acetic acid is not fermented. Gram negative.

Barker [2] also made a study of the biochemistry of the methane fermentation. He showed experimentally, using purified cultures, that the reaction proceeded as follows in the case of ethyl and butyl alcohols:

$$2C_2H_5OH + 2H_2O + CO_2 \rightarrow 2CH_3COOH + CH_4 + 2H_2O$$

$$2CH_3.CH_2.CH_2.CH_2OH + 2H_2O + CO_2 \rightarrow 2CH_3.CH_2.CH_2.COOH + CH_4 + 2H_2O$$

This led him to the conclusion that the fermentation of the alcohols resulted in their dehydrogenation and the subsequent reduction of carbon dioxide. Thus it is quite possible to generalize this result, as van Niel has done, to include all methane fermentations. The general equation for the methane fermentation would therefore be:

$$4H_2A + CO_2 \rightarrow 4A + CH_4 + 2H_2O$$

in which $H_2A$ represents any organic compound, which can be activated by the methane-producing bacteria so that it can act as a hydrogen donator for the reduction of carbon dioxide. The probable mechanism for the methane fermentation of acetic acid was then regarded as:

$$CH_3COOH + 2H_2O + CO_2 \rightarrow 2CO_2 + CH_4 + 2H_2O$$

Since pure cultures of the organisms have not as yet been obtained it is not certain that these methane-producing bacteria are able to bring about a reduction of carbon dioxide with hydrogen to methane without the aid of an associated microflora.

With the fundamental information available, work was undertaken to develop a method for the enumeration of certain methane-producing bacteria. Studies were made on their reaction to varying pH, temperature, concentration of the organic substrate, yeast extract and inert materials in the culture medium.

## Experimental

*Media.*—The classification of the four methane-producing organisms which was presented showed that enriched or purified cultures of three of the organisms could ferment calcium acetate and calcium butyrate with methane production while the fourth produced the gas from ethyl alcohol. Gasometric analyses showed the ratio $CH_4 : CO_2$ to be close to 4:1 when each organic substrate was fermented by inoculating with an enriched culture or with digesting sewage solids. The methane-producing organisms described appear to be the only organisms capable of fermenting acetate, butyrate and ethyl alcohol under anaerobic conditions. These substances were incorporated in the media as the organic

substrate. The media proposed by Barker [1] was modified in order to speed up the growth of the organisms. It consisted of:

| | | |
|---|---|---|
| $NH_4Cl$ | 0.1 | per cent |
| $K_2HPO_4$ | 0.04 | per cent |
| $MgCl_2$ | 0.01 | per cent |
| Organic substrate | 1.0 | per cent |
| Yeast extract (Bacto) | 0.003 | per cent |
| Tap water | 100 | ml |
| pH | 7.0 | |

When ethyl alcohol was used it was necessary to add one gram of $CaCO_3$ per 100 ml. of media to neutralize the acetic acid which was formed.

To remove all traces of oxygen the sterile medium was heated in steam prior to inoculation, cooled to 40° C. and a sterile solution containing one per cent of $Na_2S.9H_2O$ and five per cent of $Na_2CO_3$ (3 c.c. of this solution to each 100 ml. of medium) was added. Sodium sulfide aided in maintaining anaerobic conditions while the carbonate acted as a source of carbon dioxide. The pH was adjusted to 7.0 with sterile hydrochloric acid solution. The media was then transferred aseptically to sterile tubes for inoculation and dilution purposes.

It was necessary to make many inoculations in these studies. Agar shake cultures proved unsatisfactory due to the difficulty in handling. Anaerobic agar plates were also unsuccessful for enumeration purposes due to disruption of the agar by the gas formed and failure of the organisms to show visible colonial growth. Test tubes, containing inverted vials for gas collection in a liquid medium, were found to be most practicable. The test tubes, each containing an inverted gas vial and cotton plug, were sterilized prior to adding the sterile medium. They were inoculated with the appropriate dilution of sample, immediately sealed with "vas-par," and placed in an incubator at 35° C. All inoculations were made in duplicate and an estimation of numbers present made by use of the tables for "most probable numbers of bacteria." [3] A tube was considered positive when the inverted vial contained definite evidence of gas production.

The dilution tubes consisted of sterile, rubber-stoppered test tubes to which a measured amount of medium was added. The medium used as the diluent was the same as that into which the sample was to be inoculated. The purpose of this was to eliminate as far as possible too severe changes in environment.

*Period of Incubation.*—Several investigators have observed that the length of time necessary for the methane-producing organisms studied to produce visible evidence of their presence, in the form of gas formation, was a function of the numbers of organisms inoculated into a medium. Barker [1] noted the time required for a series of dilutions to produce gas when 0.5 ml. of sediment from an actively fermenting purified enrichment culture of the organisms was inoculated into agar shake cultures. It was not quite clear just what his final dilutions were nor for which organisms the time relationships were established.

It would be of value to speed up the rate of development of the methane-producing organisms in the synthetic media and thus a growth-promoting substance was added in the form of yeast-extract (Bacto). Table I gives the time relationships which were found when serial dilutions of actively gasifying sewage solids (4.1 per cent) were inoculated into liquid media of calcium acetate, calcium butyrate and ethyl alcohol with and without yeast-extract and incubated at 35° C. The concentration of yeast-extract used was 30 p.p.m. The first dilution contained 0.1 ml. of sludge (well-shaken before sampling) per cubic centimeter of medium and each consecutive dilution diminished the previous one ten-fold.

The speeding up of growth, especially in the higher dilutions, was evident when yeast-extract was incorporated in the media. The results also showed that the organisms which formed gas from ethyl alcohol did so faster than those which attacked acetate and butyrate.

TABLE I.—*Comparison of Time Required to Show Gas Production When Serial Dilutions of Digesting Sewage Solids Were Inoculated Into Synthetic Media With and Without Yeast Extract*

| Dilution (milliliters) | Time to Produce Gas (days) | | | |
|---|---|---|---|---|
| | No Yeast Extract | | Yeast Extract | |
| | Acetate and Butyrate | Ethyl Alcohol | Acetate and Butyrate | Ethyl Alcohol |
| 0.1–0.01 | 6–17 | 3–10 | 3–14 | 2–7 |
| 0.001 | 20–36 | 6–13 | 14–28 | 4–11 |
| 0.0001 | 24–41 | 16–27 | 18–35 | 7–18 |
| 0.00001 | 39–100 | 20–34 | 21–42 | 10–26 |
| 0.000001 | 60–140 | 30–43 | 28–50 | 14–32 |
| 0.0000001 | 75 and up | 38–53 | 37–62 | 17–39 |

It was thought that possibly the small amount of yeast extract was being utilized as a food by the bacteria to form gas. The following observations show, however, that such was not the case.

1. Inoculation of media with and without yeast-extract with portions of the same sludge sample, gave the same final count of organisms, except that gas-formation was evidenced much more rapidly in the media with yeast extract.
2. Media composed of the usual salts and 30 p.p.m. of yeast-extract with no organic substrate did not produce visible evidence of gas when inoculated with digesting solids.
3. Gas analyses showed that with or without yeast-extract the ratios of $CH_4 : CO_2$ were the same.
4. Microscopic examination revealed the same organisms to be present in both cases.

A series of inoculated dilutions must be incubated until the last negative dilution has passed the time limit indicated in Table I and there is no longer any possibility of the inoculation being positive.

*pH.*—It was thought desirable to determine the optimum hydrogen-ion concentration at which the organisms develop in the various media. The pH of the three media was adjusted with sterile hydrochloric acid or sterile sodium hydroxide, as required, and checked on an aliquot with a Beckman electrometric apparatus.

To determine the optimum pH for the ethyl alcohol organisms it was necessary to remove the $CaCO_3$ from the medium. The medium was prepared and adjusted to different pH values with HCl and NaOH omitting the $CaCO_3$. To this was then added varying amounts of the

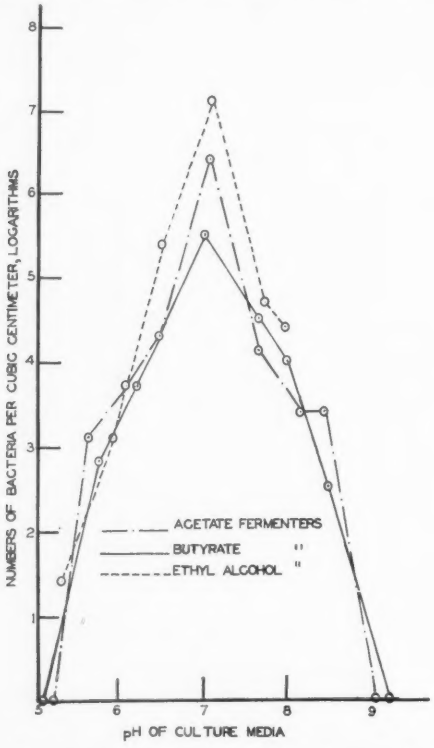


FIG. 1.—Effect of pH of the culture on the growth of methane-producing bacteria incubated at 35° C.

Sörensen buffer solution (1/15 mol $NaH_2PO_4$ and 1/10 mol $Na_2HPO_4$) in order to maintain the various pH values. Only a limited range could be covered. The media were made up in such a way that the addition of the buffer solution did not change the final concentration of nutrients. The initial and final pH, after fermentation, was checked on the Beckman potentiometer and did not change in a single instance. The media were inoculated with serial dilutions from a rapidly gasifying sludge digestion mixture.

The results, which are presented in Fig. 1, show that the optimum pH for the fermentation of calcium acetate, calcium butyrate and ethyl

alcohol to methane at 35° C. is very close to 7.0. At pH values on either side of this point there was a sharp decline in the numbers of organisms fermenting these substrates.

*Temperature.*—The optimum temperature at which the methane-forming organisms from a digesting sludge at 20° grow in liquid media was determined by inoculation of portions of the same sample of digesting sewage solids into the three media at a pH of 7.0 and incubating at

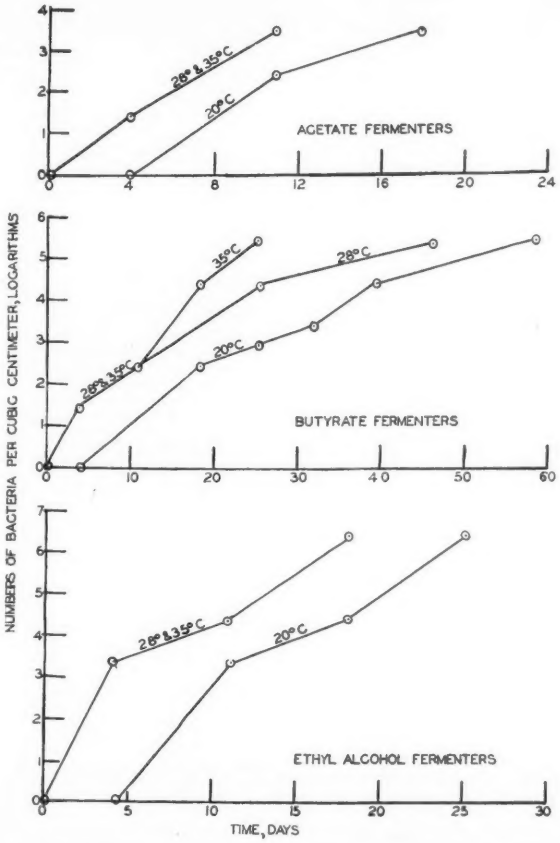


FIG. 2.—Effect of temperature on the growth of methane-producing bacteria.

20°, 28,° 35° and 55° C. Organisms from the sludge digesting at 20° C. would not develop gas when placed at 55° C. The optimum temperature was in the range 28°–35° C. as indicated by the results presented in Fig. 2.

*Use of Inert Materials in the Media.*—It will be shown in a subsequent paper that the methane-producing organisms tend to concentrate in the sludge phase rather than the liquid portion of digestion mixtures. Other investigators [4] have added asbestos and other inert materials to

synthetic media to facilitate the growth of methane-producing organisms. Thus it was thought that an inert material added to the medium might speed up growth of the organisms. Culture media to which asbestos was added gave evidence of gas production somewhat earlier than those to which kaolin or no inert material was added. This was due to the fact that the asbestos fibers trapped the small gas bubbles which were formed and on shaking the tube a small but noticeable bubble was released and the tube could be called positive. The reduction in

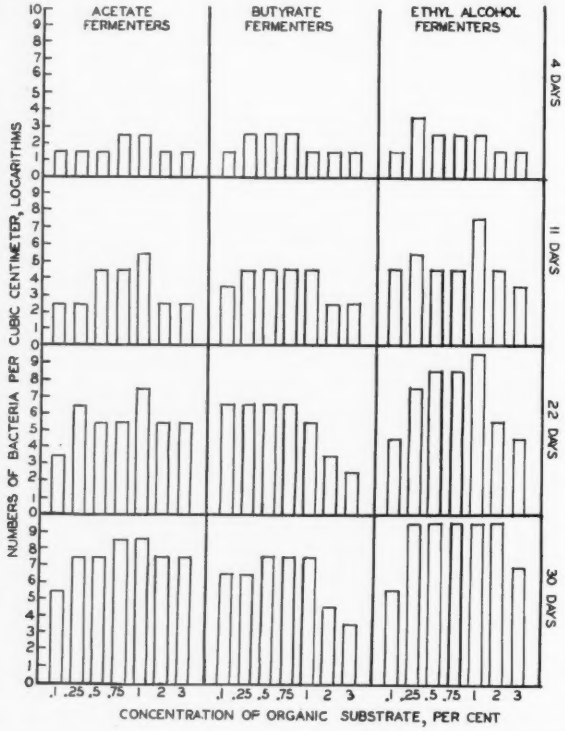


FIG. 3.—Effect of the concentration of the organic substrate of the culture media on the growth of methane-producing bacteria at 35° C.

time of inoculation was not found to be sufficient to warrant the addition of asbestos to the medium in the method of enumeration which was used.

*Concentration of the Organic Substrate.*—An experiment was performed to determine the optimum concentration of the organic substrate for the growth of methane-producing bacteria at a pH of 7.0. Media containing varying concentrations of the organic substrate were inoculated with dilutions containing approximately the same number of organisms taken from a rapidly gasifying culture of the particular substrate being tested. Thirty days was taken as the final count, since after this period no further gas development was noticed in any of the remaining dilutions. The results shown in Fig. 3 indicated that for a

maximum development of methane-producing organisms on the organic substrates tested a concentration of 0.75–1.0 per cent should be used.

## Discussion

The methane-producing bacteria play a decidedly important role in the digestion and stabilization of sewage solids. It is of value to have a method for determining the numbers of these organisms in digesting sewage solids as well as under various changes in environmental conditions such as temperature, pH air contact, and other physical and chemical changes. With this in mind a method was developed for enumerating these organisms.

That the methods employed gave results of value was shown in several cases. Perhaps the best check on the method was indicated in Fig. 2. Three equal samples from the same sludge were inoculated into media and placed at different temperatures. Although the rate of growth was faster at higher temperatures, the same final counts were obtained at all temperatures in the respective culture media. Again in the experiment on the concentration of the organic substrate Fig. 3 showed that within certain ranges of substrate concentration duplicate inoculations gave the same final count. Thus it became evident that the results obtained for the numbers of methane-producing organisms were not merely chance results, but actually were capable of duplication.

The temperature experiments further indicated that the rate of growth of the organisms in a culture medium was about the same at 28° C. as at 35° C., with the exception of the butyrate-fermenting organisms. The rate of growth at 28° C. was considerably faster than at 20° C. Studies on the effect of temperature on the rate of digestion have indicated that the digestion is accelerated by increasing temperatures up to about 28 to 32° C. Further increase of temperature to 40° C. does not increase the rate of digestion. The inoculations from a 20° sludge placed in the media at 55° C. showed no growth, indicating that probably different organisms are responsible for methane production at the higher temperature.

The results showed that it was justifiable to remove samples from a 20° C. digesting sludge and to incubate the cultures at 35° C., since the same final numbers of organisms were observed at both temperatures. The higher temperature merely accelerated the rate of growth.

The experiments on the optimum pH for the culture media showed it to be very close to neutrality for maximum growth. The general range of pH during maximum sludge digestion is 7.2–7.8. The numbers of organisms were adversely effected on both sides of the neutrality point to an equal extent. In other words, reducing the pH value to 6.5 had as great an adverse effect as increasing it to 7.5. Since, however, the action of methane bacteria is dependent on the prior activity of other groups of bacteria it may well be that optimum pH for the continued activity of all groups is somewhat on the alkaline side of neutrality, as

shown in practical operation. However, when considerable amounts of salts are present in the original water the optimum pH may be lower.

It is still impossible to report that any of the methane-producing organisms have been isolated in pure culture. The studies which have been presented in the experimental part of this paper are not concerned with single organisms which ferment acetate or butyrate and ethyl alcohol with the production of methane. Microscopic examinations of cultures of the acetate and butyrate media showed a sarcina, a coccus and a rod-shaped organism to be present at times. The alcohol media seemed to support only the growth of a long, somewhat bent, slender bacterium. This organism corresponded to the *Methanobacterium Omelianskii* described by Barker.[1] In a more recent study on his organism [5] he found that when an associated spore-forming bacterium was present, methane, acetic, butyric and caproic acids were formed.

Thus the counts for the alcohol-fermenting organism probably represent only a single species of methane-fermenting organism. On the other hand the counts in acetate and butyrate media may represent three or more species of methane-producers. Nevertheless, the counts are of value since they give us an idea of the relative numbers of organisms present during sludge digestion, which are capable of producing methane.

It is of interest to note that the concentration of the organic substrate had a considerable effect on the maximum numbers of organisms. Generally concentrations of the organic substrate of 0.75 to 1.0 per cent gave the highest numbers. In concentrations below and above fewer numbers of organisms developed. A concentration of 0.1 per cent of food material would limit the numbers of organisms due to the insufficient amount of food material. The limiting influence of the highest concentrations could be explained either by the unfavorable physical environment created (surface tension, osmotic pressure, etc.) or by the concentration of waste products.

These organisms apparently grow at a very slow rate and their rate of development is dependent on the initial numbers. If they could grow at a rate equal to that of other saprophytic bacteria, proper inoculation in sludge digestion would not be so important. Within a short time the organisms in the fresh solids would multiply sufficiently (with proper environmental control such as pH, temperature regulations) to make the use of ripe sludge unnecessary. Thus their slow rate of development makes not only the artificial inoculation by the use of ripe sludge a necessity for economical sludge digestion but also explains the beneficial effect of retaining large volumes of sludge in the tank.

From a laboratory standpoint the use of a growth-stimulating substance such as yeast extract has been of great practical value by reducing the time necessary for incubation. It seems doubtful, however, whether the artificial addition of such substances to digesting sludge would similarly reduce the time, since in a complex material such as sludge it would be reasonable to expect that small quantities of a num-

ber of growth-stimulating substances were either present originally in the solids or produced as a result of bacterial action.

## Summary

1. A method was developed for the enumeration of methane-producing bacteria in sewage solids.

2. The pH optimum for methane producing organisms is at 7.0. The optimum sharply drops at both sides of neutrality.

3. The optimum temperature for the development of methane bacteria is 28° C. Neither the rate of development nor the ultimate numbers are effected by increasing the temperature up to 35° C. The ultimate numbers at 20° C. are the same as at 28° C. but the time required is considerably longer.

4. The concentration of the organic substrate (acetate, butyrate and ethyl alcohol) effects the maximum number of these organisms. A concentration of 0.75 to 1.0 per cent of these substances gives the highest numbers. The numbers drop either with two low (0.1 per cent) or too high (3.0 per cent) concentration.

5. The addition of yeast-extract was of considerable value in speeding up the rate of growth of the methane-producing organisms in culture media.

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# STUDIES ON THE METHANE-PRODUCING BACTERIA *

## II. ENUMERATION IN DIGESTING SEWAGE SOLIDS

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### Introduction

The digestion or stabilization of sewage solids is a fermentation process in which a decidedly diversified group of micro-organisms capable of existing under anaerobic conditions take part. Rudolfs [1] has divided the process into three stages; intensive acid production, acid digestion, and digestion of more resistant materials. The digestion of the more complex compounds such as proteins, fats, sugars and cellulose, which are attacked by the common saprophytic anaerobes, produce the lower acids, and probably other compounds, which will then secondarily undergo a methane fermentation resulting in stabilization of the degradation products.

Most of the investigations on sludge digestion have been concerned with the chemical and biochemical aspects of the problem. Information has been made available on various end-products or results of the process and thus a certain amount of control can be exercised over the process by noting changes in these results. Little is known about the methane-producing organisms which are responsible for stabilizing the products formed by the hydrolytic flora. A knowledge of the part played by these organisms is essential for a proper understanding of sludge digestion and is especially important in modern plants where use is made of the combustible gases formed.

In a previous paper a method developed for the enumeration of methane-producing bacteria was described.[2] This method was used to follow the changes in the numbers of these organisms during the digestion of limed, seeded and untreated sewage solids. A study was also made of the distribution of the methane-producing organisms in the liquid and sludge phases of digesting sewage solids.

### Experimental

*Bacteriological Technique.*—The methods and culture media used were the same as given in a previous paper.[2] All dilutions were inoculated in duplicate and determination of the number of organisms present made by using tables for "most probable numbers of bacteria." The inoculated cultures were incubated at 35° C.

*Preparation of the Sewage Solids for Digestion.*—Fresh sewage solids were obtained from a plant receiving domestic waste only. In order to make the solids more homogenous and to facilitate future

* Journal Series Paper, N. J. Agricultural Experiment Station, New Brunswick, N. J., Dept. Water and Sewage Research.

sampling they were put through a "Disposal" garbage grinder. The ground material had a solids concentration of 4.2 per cent of which 56 per cent was volatile. The high ash content was probably due to infiltration and the lack of facilities for grit removal. Counts of methane-producing bacteria were made on digesting limed, seeded and untreated sewage solids at intervals. The material which was limed received daily additions of calcium hydroxide to a pH value of 7.2–7.4 until the pH value remained in this range. The seeded material consisted of fresh solids plus ripe sludge mixed in the ratios indicated in Figs. 2 and 3. All digestion samples were incubated at 22° C.

A portion of each sample was connected to a gas-collecting device. The remainder of each sample was then divided into 100 ml. portions

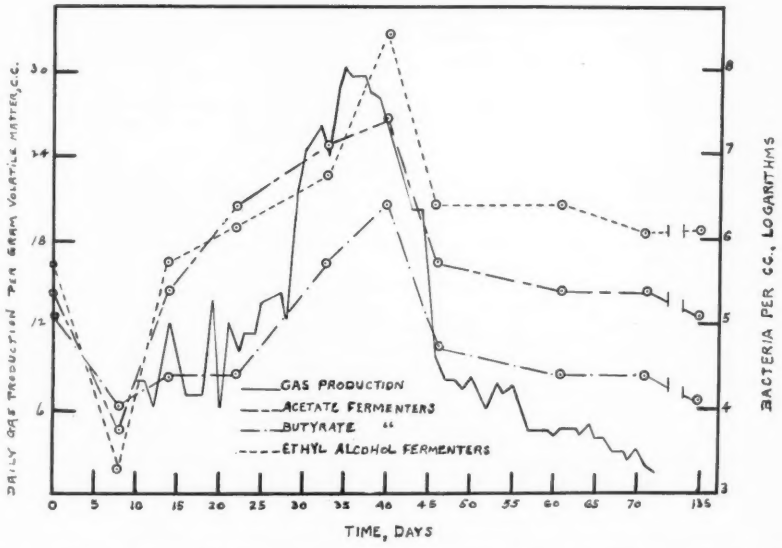


FIG. 1.—Methane-producing bacteria and daily gas production during digestion of limed solids at 22° C.

and stoppered with Bunsen valves. These portions were used to inoculate the media for the purpose of counting the methane-producing organisms present which could ferment acetate, butyrate and ethyl alcohol. They were shaken, sampled with a sterile, broken-tipped pipette, and then discarded.

## RESULTS

*Limed Solids.*—The data presented in Fig. 1 show the daily gas production and number of methane-producing bacteria, which ferment the substrates indicated, in a sample of limed solids. Gas collection was started after 10 days when no further additions of lime were necessary to maintain the proper pH. The bacterial curves showed a considerable drop in the numbers of methane-producing organisms present

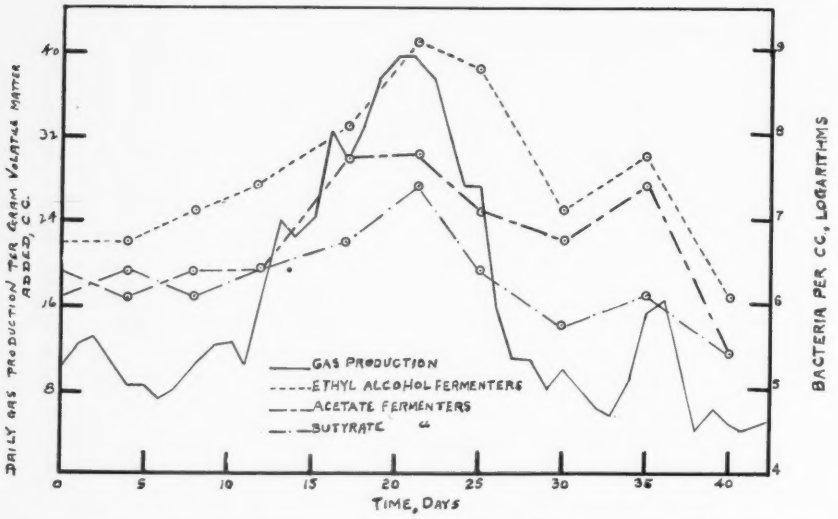


FIG. 2.—Methane-producing bacteria and daily gas production during digestion of a fresh solids—ripe sludge mixture (ratio 2: 1 on dry volatile matter basis) at 22° C.

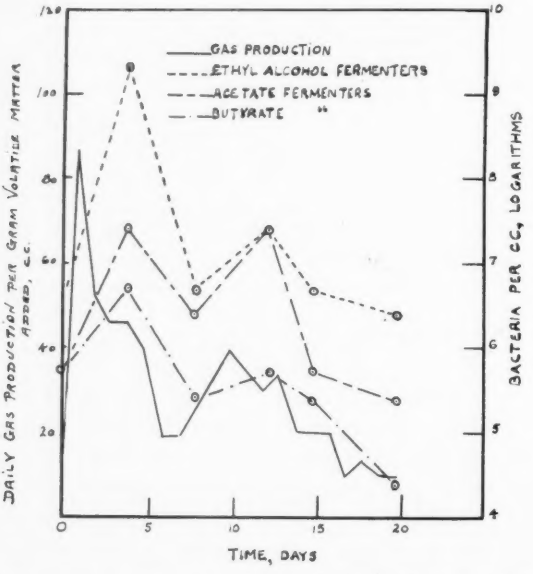


FIG. 3.—Methane-producing bacteria and daily gas production during digestion of a fresh solids—ripe sludge mixture (ratio 1: 1 on dry volatile matter basis) at 22° C.

during the liming or acid stage. The numbers increased after the acid digestion period and reached a maximum at or shortly after the peak of gas production. The numbers of methane-producing organisms then fell off rapidly with an accompanying decrease in gas production. A

constant level with only slight changes in numbers existed for a period of 90 days thereafter.

*Seeded Solids.*—Figs. 2 and 3 shows the daily gas production and types of methane-producing bacteria in two samples of fresh solids seeded with different ratios of ripe sludge. In both cases there was no sharp decrease in the numbers of the organisms originally present. The maximum numbers occurred at or close to the peak of the gas production. With the decline in gas production there was a sharp decline in the number of methane-producing organisms. A slight secondary rise in gas production was accompanied by a noticeable increase in the numbers of organisms.

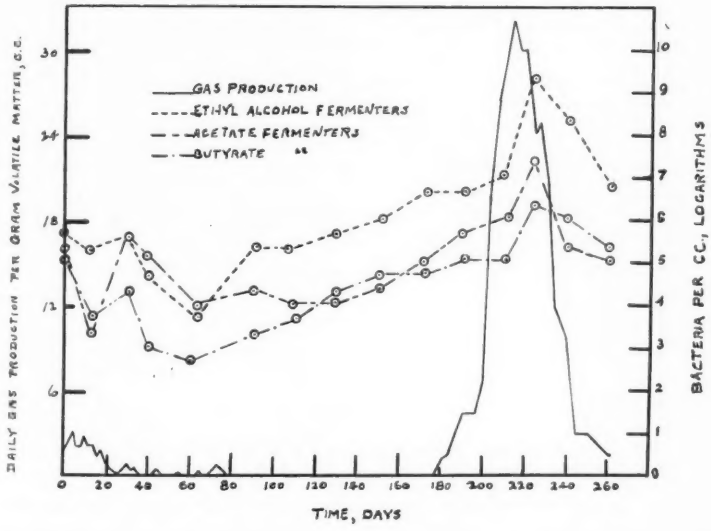


FIG. 4.—Methane-producing bacteria and daily gas production during digestion of untreated solids at 22° C.

*Untreated Solids.*—The curves presented in Fig. 4 for the untreated solids follow the same general trend as those for the limed solids, except that a longer period of time was required for digestion. There was an initial decrease, of the original numbers present, during the acid stage of digestion with a subsequent rise until the peak of gasification was reached and then a sharp decrease in numbers.

*Distribution of Methane-Producing Bacteria in Digesting Sewage Solids.*—A sample of solids which was gasifying rapidly and another which had passed the peak of gas production were used to determine the relative numbers of methane-producing bacteria in the sludge and liquid portions. In both samples there was a well marked division into liquid and sludge portions.

Analyses of the two sludges were as follows:

| | Solids Concentration (Per cent) | |
|---|---|---|
| | Sludge | Supernatant Liquor |
| Rapidly Gasifying | 3.6 | 0.23 |
| Slowly Gasifying | 2.5 | 0.21 |

The results presented in Table I indicated that there were considerably more organisms in the sludge phase of digesting solids than in the supernatant liquor when the numbers were expressed per cubic centimeter or per gram of solids.

TABLE I.—*Methane-producing Bacteria in the Liquid and Sludge Portions of Rapidly and Slowly Gasifying Sewage Solids*

| Organic Substrates Fermented | Organisms per Cubic Centimeter (× 1000) | | Organisms per Gram Solids (× 1000) | |
|---|---|---|---|---|
| | Rapidly Gasifying | Slowly Gasifying | Rapidly Gasifying | Slowly Gasifying |
| Supernatant liquor | | | | |
| Acetate—Fermenters | 250 | 6 | 125,000 | 3,000 |
| Butyrate—Fermenters | 2.5 | 0.6 | 1,250 | 300 |
| Ethyl Alcohol—Fermenters | 25 | 2.5 | 12,500 | 1,250 |
| Sludge phase | | | | |
| Acetate—Fermenters | 25,000 | 600 | 700,000 | 24,000 |
| Butyrate—Fermenters | 6,000 | 60 | 170,000 | 2,400 |
| Ethyl Alcohol—Fermenters | 250,000 | 1,300 | 7,000,000 | 52,000 |

## DISCUSSION

The remarkably close relationship between the gas production and the numbers of the different types of methane-producing organisms has been one of the outstanding features of this study. In fact the correlation has been so close that it is possible to determine the stage of digestion from the bacterial counts. The value of this observation does not, at the present time, lie in the possible use of the numbers of methane organisms, instead of gas production, as an index of digestion but the increased confidence that it inspired on the validity of the method of enumeration of methane bacteria. It should be observed that in certain cases there was a difference of a few days between gas production values and bacterial numbers. Still closer values might have been obtained if bacterial enumerations had been made more frequently.

It was not surprising that the untreated solids during the early stage of digestion manifested a decided drop in the numbers of methane-producing bacteria. It is well known that during this period the acidity is high and the pH value is low. These organisms in culture media have been shown to be very sensitive to small changes of pH value from the neutrality point.[2] In limed solids, during the period where lime additions were necessary to maintain the pH value at 7.2–7.4, a similar decrease in bacterial numbers took place. In spite of the daily attempts

to adjust the pH value, part of the day the solids were digesting under acid conditions. It is possible to attribute the decrease in numbers to this circumstance although other factors such as the effect of some toxic product during this period should also be considered. It is to be noted, however, that after the period of acid digestion when lime additions became unnecessary the bacterial numbers steadily increased. Furthermore, the initial drop in bacterial numbers did not take place in the seeded solids. These results emphasized the importance of environmental conditions in the stabilization of sewage solids by the methane-producing bacteria. Maximum growth of these organisms did not occur until the environment was favorable.

The simultaneous decrease of the numbers of bacteria with gas production after the digestion was complete should be explained on the basis of the exhaustion of the food for these organisms. But once a certain level is reached, due to the alteration of the food factor, the organisms maintain their values in the ripe sludge for a period of at least three months without further appreciable decrease.

In Table II are given the average numbers of methane fermenting bacteria originally present in a number of fresh solids and ripe sludges

TABLE II.—*Average Numbers of Methane Producing Organisms at the Peak of Gasification in Fresh Solids and Ripe Sludge*

(Average of 6 samples)

| Organic Substrates Fermented | Organisms per Gram Solids (× 1000) | | |
|---|---|---|---|
| | Peak of Gasification | Fresh Solids | Ripe Sludge |
| Acetate—Fermenters | 950,000 | 6,250 | 12,000 |
| Butyrate—Fermenters | 252,000 | 3,250 | 5,400 |
| Ethyl Alcohol—Fermenters | 4,600,000 | 15,000 | 121,000 |
| | Organisms per Cubic Centimeter (× 1000) | | |
| Acetate—Fermenters | 34,000 | 250 | 308 |
| Butyrate—Fermenters | 9,000 | 130 | 135 |
| Ethyl Alcohol—Fermenters | 1,638,000 | 600 | 2,775 |

so far tested as well as the average numbers of various digesting mixtures at their maximum level. It is striking that the numbers on the basis of dry solids are relatively high in fresh solids as compared with ripe sludge. The difference in numbers occurs at the peak of gasification.

From the standpoint of introduction of maximum numbers of methane-producing bacteria the sludge at the peak of maximum activity is preferable. Previous work,[3] using gas production as an index for proper seeding condition of sludge, showed that best results were obtained when the sludge was just past the peak of gasification and for about a month thereafter. Thus it would appear that the chief value of ripe sludge lies in the production of favorable environmental condi-

tions and that the slow rate of digestion of fresh solids is not due primarily to the paucity of methane-fermenting organisms, but to the lack of favorable environmental conditions.

Table III is presented to give some idea of the relative increases in the numbers of methane-producing organisms by noting the maximum and minimum counts observed, in the culture media used, up to the peak of gasification. The data was taken from the results presented in Fig. 1–4.

TABLE III.—*Maximum and Minimum Numbers, Up to the Peak of Gasification, of Methane-Producing Bacteria (× 1000 per cubic centimeter) Obtained During Digestion of Sewage Solids*

| Sample | Acetate—Fermenters | | | Butyrate—Fermenters | | | Ethyl Alcohol—Fermenters | | |
|---|---|---|---|---|---|---|---|---|---|
| | Max. | Min. | Increase | Max. | Min. | Increase | Max. | Min. | Increase |
| Limed | 25,000 | 6 | 4,160 | 2,500 | 13 | 192 | 250,000 | 2.5 | 100,000 |
| Seeded (2 : 1 ratio) | 60,000 | 1,300 | 46 | 25,000 | 1,300 | 19 | 1,300,000 | 6,000 | 216 |
| Seeded (1 : 2 ratio) | 25,000 | 600 | 41 | 6,000 | 600 | 10 | 2,500,000 | 2,500 | 1,000 |
| Untreated | 25,000 | 2.5 | 10,000 | 2,500 | 0.6 | 4,160 | 2,500,000 | 6 | 416,666 |

It was evident from Table III that the greatest increase in numbers of organisms was made by those fermenting ethyl alcohol. Apparently these bacteria must be capable of utilizing certain materials in the digesting sludge very readily. The maximum numbers of organisms found which grew on the three substrates was lowest in the limed solids. The maximum numbers in the untreated solids were more similar to the two ripe sludge mixtures than to the limed solids. Not much stock can be placed in this, however, since it was impossible to sample the materials daily and the maximum and minimum counts may not necessarily be the true ones. Reference to Fig. 1–4 show that the samplings were not always made at the peak of gasification and thus even greater counts than the ones obtained may have been attained in the various sludges.

It should be borne in mind that the numbers obtained with the substrates cannot be added together to obtain the total number of methane bacteria since the same type of organism may grow in more than one substrate. It should also be pointed out that the maximum numbers of methane-producing bacteria obtained in the different solids are much higher than any previously reported values obtained on standard bacterial media such as nutrient agar and special media such as broth. As far as methane organisms are concerned it is felt that previous counts obtained with such media included only a small fraction if any of the specialized bacteria capable of producing methane.

The results presented in Table I indicate that the methane-producing organisms studied were concentrated in the sludge phase of the digesting solids. The nutrient materials which they utilize, on the other hand, are water soluble and would thus be in solution in the supernatant liquor. The organisms may be in the sludge phase as the result of

sedimentation or due to attachment to the fibrous, solid substances present. Nevertheless, there were a certain number of the organisms in the supernatant liquor probably due to the circulation caused by the gas bubbles as they came up from the bottom. This circulation would also bring nutrients to the organisms in the sludge phase. It would be interesting to determine whether solid material is an aid in the functioning of methane-producing bacteria. Results presented in a previous paper [2] showed that asbestos fibres added to cultures did not greatly decrease the time required for the organisms to show evidence of gas production, but on the other hand, the asbestos may permit a greater concentration of organism in a given culture.

Do the organisms producing methane from ethyl alcohol in the culture medium, which are the most predominant group, grow on alcohol in the sludge substrate? It is known that a number of substances which are commonly present in fresh solids such as cellulose, proteins, fats and other carbohydrates, when fermented under anaerobic conditions, will produce ethyl alcohol. Buswell [4] showed that ethyl alcohol was readily converted to methane when added to ripe sludge. We have been able to detect the presence of small amounts of alcohol (25–200 p.p.m.) during the digestion of fresh solids. That the quantity is not higher may be caused by methane organisms readily converting it to methane as soon as it is formed. In spite of these evidences there still is the possibility that these organisms which ferment ethyl alcohol to methane in synthetic medium utilize another substance in the digestion of sewage solids.

The probability is great that acetate and butyrate are utilized in methane production since these substances are known to be present in the different phases of sludge digestion.[5] These acids arise from the hydrolysis of certain fats, proteins and corbohydrates. Enriched cultures of various cellulose fermenting bacteria, when added to sterile fresh solids were able to convert 5.3–12 per cent of the original cellulose (0.7 gm. per 100 ml.) to acetic acid and 0.9–2.4 per cent to butyric acid (unpublished results).

## Summary and Conclusions

Using the technique described in the first paper of this series the numbers of methane-producing bacteria present during the course of digestion of seeded, limed and untreated solids were determined. The results showed that the organisms capable of producing methane from calcium acetate, butyrate and ethyl alcohol in synthetic medium were present in digesting sewage solids and their numbers were an indicator of the course of digestion. The numbers were only slightly higher in ripe sludge than fresh solids. During the course of digestion of either seeded or unseeded solids the numbers increased greatly, attaining a maximum. Their numbers thereafter decreased rapidly and became more or less stationary for a period of three months. Both in the limed and unlimed solids the numbers of the organisms decreased during the

acid digestion phase. Such a decrease did not take place during the digestion of seeded solids. The course of development of the methane-producing bacteria in digesting sewage solids emphasized once again the importance of producing proper environmental conditions for sludge digestion. The numbers obtained were far in excess of any other estimation of bacterial numbers in sludge digestion. There were more methane organisms both on volume or dry solids basis in the sludge phase than in the liquid phase.

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# THE DISSOLVED OXYGEN SAG—AN ANALYSIS

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When sewage or other decomposable waste material is discharged into a receiving water, such as a stream, the interplay of biochemical oxygen demand and of atmospheric reaeration creates a spoon-shaped profile of the dissolved-oxygen deficit along the course of the stream known as "the dissolved oxygen sag" (Fig. 1). The general mathematical properties of

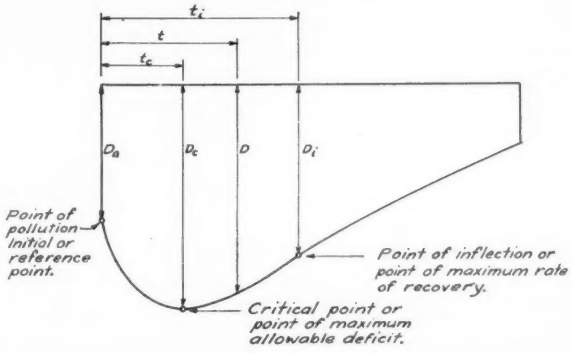


Fig. 1.—Characteristic points and coördinates of the dissolved-oxygen sag.

the sag curve have been developed in the classical studies of Streeter and Phelps and their co-workers in the U. S. Public Health Service.*

It is the purpose of this paper to present a systematic analysis of the dissolved-oxygen sag because such an analysis yields results, so far unreported in the literature, that simplify the analytical as well as the graphical solution of certain engineering problems connected with the disposal of municipal and industrial wastes in receiving waters and give a general concept of the permissible loading of receiving waters. This paper is divided into four parts:

*A*. Rapid determination of the coördinates of two characteristic points of the dissolved oxygen sag.
*B*. Delimitation of the pollutional load that can be placed upon receiving waters.
*C*. Correlation between dilution requirements and pollutional load.
*D*. Non-mathematical generalization of the allowable loading of receiving waters.

*Notation.*—Adopting, so far as applicable, the notation employed by Streeter and Phelps (see Figure 1):

* See especially *This Journal*, **7** (1935), 251 and 534, and "Modern Sewage Disposal," Chapter 17, Fed. of Sew. Works Assn's (1938).

$D_a$ = the dissolved-oxygen deficit at the point of pollution, initial or reference point, *i.e.* the initial deficit of the receiving water at zero time;
$D$ = the deficit at any point distant a time of flow $t$ from the reference point;
$D_c$ = the maximum, or critical, deficit at the lowest point of the sag distant a time $t_c$ from the reference point;
$D_i$ = the deficit at the point of inflection in the sag distant a time $t_i$ from the reference point;
$L_a$ = the first-stage biochemical oxygen demand (B.O.D.) at the reference point;
$L_e$ = the first-stage B.O.D. on a per capita basis;
$X$ = the biochemical oxygen demand exerted in time $t$;
$L = L_a - X$ = the B.O.D. remaining to be exerted at time $t$;
$k_1 = 0.4343\,K_1$ = the deoxygenation constant or reaction-velocity constant of the B.O.D.;
$k_2 = 0.4343\,K_2$ = the reaeration constant or reaction-velocity constant of oxygen absorption from the atmosphere;
$f = \frac{k_2}{k_1} = \frac{K_2}{K_1}$ = the self-purification constant or reaeration-deoxygenation ratio, and
$S$ = the dissolved-oxygen saturation value at any temperature $T$.

## Coördinates of Characteristic Points

From an engineering standpoint, the dissolved-oxygen sag possesses two particularly interesting points:

*a*. The point of maximum deficit, or critical point; and
*b*. The point of maximum rate of recovery.

In a mathematical sense, the point of maximum deficit is identified by the maximum of the dissolved-oxygen profile, while the point of maximum rate of recovery is identified by the point of inflection of the profile. It should be noted that the ordinates, $D$, of the profile are plotted downward, rather than upward; also that the maximum deficit coincides, of necessity, with the minimum dissolved-oxygen residual. Since the coördinates of any point on the sag curve are time, $t$, and oxygen deficit, $D$, the critical point is defined by $\frac{dD}{dt} = 0$ and $\frac{d^2D}{dt^2} < 0$, while the point of inflection is given by $\frac{d^2D}{dt^2} = 0$.

1. *Basic Equations.*—As formulated by Streeter and Phelps the basic differential equation for deoxygenation and reaeration is:

$$\frac{dD}{dt} = K_1L - K_2D \qquad (1a)$$

*i.e.* the rate of change in the oxygen deficit is equal to the difference between the rate of B.O.D. and the rate of reaeration. Integration yields the following equations for the oxygen sag curve:

$$D = \frac{K_1 L_a}{K_2 - K_1} (e^{-K_1 t} - e^{-K_2 t}) + D_a \cdot e^{-K_2 t} \tag{1b}$$

or

$$D = \frac{k_1 L_a}{k_2 - k_1} (10^{-k_1 t} - 10^{-k_2 t}) + D_a \cdot 10^{-k_2 t} \tag{1c}$$

For reasons that will become apparent later, the author prefers to write equation (1c) as follows:

$$D = \frac{L_a}{f - 1} \cdot 10^{-k_1 t} \left\{ 1 - 10^{-(f-1) k_1 t} \left[ 1 - (f - 1) \frac{D_a}{L_a} \right] \right\} \tag{1d}$$

For $f = 1$, or $k_2 = k_1$, equations (1b to 1d) become indeterminate. A study of the limits yields the relationship:

$$D = (2.303\, k_1 t L_a + D_a) \cdot 10^{-k_1 t} \quad \text{for} \quad f = 1 \tag{1d'}$$

2. *The Critical Point or Point of Maximum Deficit.*—The coördinates of this point are $t_c$ and $D_c$ (see Fig. 1). Taking the first derivative of equation (1b):

$$\frac{dD}{dt} = \frac{L_a}{f - 1} (- K_1 e^{-K_1 t} + K_2 e^{-K_2 t}) - K_2 D_a \cdot e^{-K_2 t} \tag{2a}$$

we can find the value of the critical time, $t_c$, by setting equation (2a) equal to zero. Dividing by the factor $\frac{L_a}{f - 1} (- K_1 e^{-K_1 t})$, and simplifying, we have:

$$e^{(K_2 - K_1) t_c} = f \left[ 1 - (f - 1) \frac{D_a}{L_a} \right] = 10^{(f-1) k_1 t_c} \tag{2b}$$

and

$$k_1 t_c = \frac{1}{f - 1} \log \left\{ f \left[ 1 - (f - 1) \frac{D_a}{L_a} \right] \right\} \tag{2c}$$

This equation, as well as equations (1b), (1c), (2a) and (2b), was first derived by Streeter and Phelps,* but the ratio, $f = \frac{k_2}{k_1}$, was not employed by them. For a value of $f = 1$, equation (2c) becomes indeterminate. Investigation of the limits yields the relationship:

$$k_1 t_c = 0.4343 \left( 1 - \frac{D_a}{L_a} \right) \quad \text{for} \quad f = 1 \tag{2c'}$$

To find the critical deficit, $D_c$, substitute

$$\frac{1}{f} = 10^{-(f-1) k_1 t_c} \left[ 1 - (f - 1) \frac{D_a}{L_a} \right]$$

from equation (2b), in equation (1d), then:

$$D_c = \frac{L_a}{f} \cdot 10^{-k_1 t_c} \tag{2d}$$

* *U. S. Public Health Bulletin* 146 (1925).

Also

$$D_c = \frac{1}{f}(L_a - X_c) \tag{2e}$$

because $L_a \cdot 10^{-k_1 t_c}$ is the B.O.D. remaining to be exerted after time $t_c$ and must equal $(L_a - X_c)$, where $X_c$ is the B.O.D. exerted during this time. The value of $k_1 t_c$ from equation (2c) may also be substituted in the logarithmic transform of equation (2d), namely:

$$\log D_c = \log \frac{L_a}{f} - k_1 t_c \tag{2f}$$

Parenthetically, equation (2d) might have been derived more directly by placing the rate of deoxygenation equal to the rate of reaeration, a condition that obtains at the critical point, or by equating (1a) to zero $(K_1 L - K_2 D = 0)$, whence

$$K_2 D_c = K_1 L_a \cdot 10^{-k_1 t_c} \qquad \text{since} \qquad L = L_a \cdot 10^{-k_1 t_c}$$

or

$$D_c = \frac{L_a}{f} \cdot 10^{-k_1 t_c}$$

3. *The Point of Inflection or Point of Maximum Rate of Recovery.*—The coördinates of this point are $t_i$ and $D_i$ (see Fig. 1). Taking the second derivative of equation (1b):

$$\frac{d^2 D}{dt^2} = \frac{L_a}{f-1}(K_1^2 e^{-K_1 t} - K_2^2 e^{-K_2 t}) + K_2^2 D_a \cdot e^{-K_2 t} \tag{3a}$$

we can find the value of the time of inflection, $t_i$, by setting equation (3a) equal to zero. Dividing by the factor $\frac{L_a}{f-1} K_1^2 e^{-K_1 t}$ and simplifying, we have:

$$e^{(K_2 - K_1) t_i} = f^2 \left[ 1 - (f-1) \frac{D_a}{L_a} \right] = 10^{(f-1) k_1 t_i} \tag{3b}$$

and

$$k_1 t_i = \frac{1}{f-1} \log \left\{ f^2 \left[ 1 - (f-1) \frac{D_a}{L_a} \right] \right\} \tag{3c}$$

For a value of $f = 1$, equation (3c) becomes indeterminate. Investigation of the limits yields the relationship:

$$k_1 t_i = 0.4343 \left( 2 - \frac{D_a}{L_a} \right) \quad \text{for} \quad f = 1 \tag{3c'}$$

To find the inflection deficit, $D_i$, substitute

$$\frac{1}{f^2} = 10^{-(f-1) k_1 t_i} \left[ 1 - (f-1) \frac{D_a}{L_a} \right]$$

from equation (3b) in equation (1d), then:

$$D_i = \frac{f+1}{f^2} L_a \cdot 10^{-k_1 t_i} \tag{3d}$$

and

$$D_i = \frac{f+1}{f^2}(L_a - X_i) \tag{3e}$$

The value of $k_1 t_i$ from equation (3c) may also be substituted in the logarithmic transform of equation (3d), namely:

$$\log D_i = \log \frac{f+1}{f^2} L_a - k_1 t_i \tag{3f}$$

4. *Relation between Point of Inflection and Critical Point.*—The coördinates of the point of inflection are calculated most readily by relating them to the coördinates of the critical point. Subtracting equation (2c) from equation (3c):

$$k_1(t_i - t_c) = \frac{1}{f-1} \log f \tag{4a}$$

and for the special case of $f = 1$,

$$k_1(t_i - t_c) = 0.4343 \tag{4a'}$$

It should be noted that equation (4a) is the same as equation (2c) when $D_a = 0$.

Dividing equation (3d) by equation (2d):

$$\frac{D_i}{D_c} = \frac{f+1}{f} \cdot 10^{-k_1(t_i - t_c)} \tag{4b}$$

Also

$$\log \frac{D_i}{D_c} = \log \frac{f+1}{f} - k_1(t_i - t_c) \tag{4c}$$

*Application of Equations.*—These equations facilitate rapid calculation of the coördinates of the oxygen sag at its two characteristic points and permit sketching the profile of the sag, as far as the point of inflection, with sufficient precision for many engineering purposes. A sample calculation follows:

*Given* $D_a = 3.2$ p.p.m.; $L_a = 20.0$ p.p.m.; $k_1 = 0.1$ at 20° C.; $k_2 = 0.24$ for a large stream such as the Ohio River;

$$\frac{D_a}{L_a} = \frac{3.2}{20.0} = 0.16; \qquad \text{and} \qquad f = \frac{0.24}{0.10} = 2.4.$$

*Find* *a.* From equation (2c):

$$k_1 t_c = \frac{1}{1.4} \log [2.4(1 - 1.4 \times 0.16)] = \frac{\log 1.86}{1.4} = \frac{0.270}{1.4} = 0.193$$

and

$$t_c = \frac{0.193}{0.1} = 1.93 \text{ days.}$$

*b.* From equation (2f):

$$\log D_c = \log \frac{20.0}{2.4} - 0.193 = 0.921 - 0.193 = 0.728$$

and

$$D_c = 5.3 \text{ p.p.m.}$$

*c.* From equation (4a):

$$k_1(t_i - t_c) = \frac{1}{1.4} \log 2.4 = \frac{0.380}{1.4} = 0.272$$

and

$$t_i = 1.93 + 2.72 = 4.65 \text{ days.}$$

*d.* From equation (4c):

$$\log \frac{D_i}{D_c} = \log \frac{3.4}{2.4} - 0.272 = 0.152 - 0.272 = -0.120 = 0.880 - 1$$

and

$$D_i = 5.3 \times 0.76 = 4.0 \text{ p.p.m.}$$

*Graphical Presentation and Solution of Equations.*—Equations (2c) and (2d), and by suitable adaptation also equations (3d) and (4a), lend themselves to graphical presentation as shown in Fig. 2. For purposes of

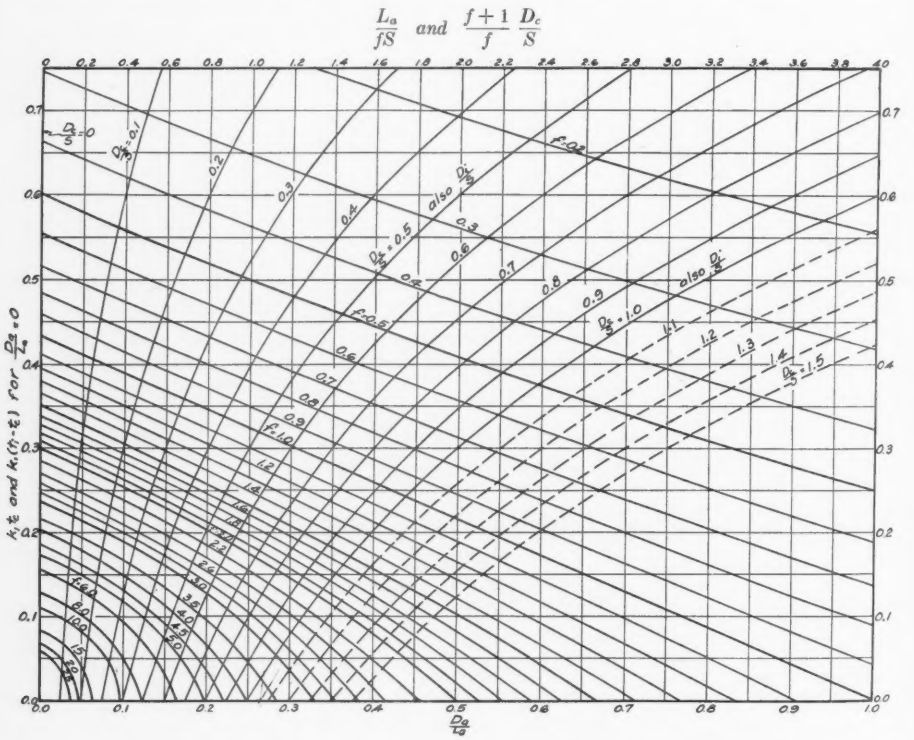


FIG. 2.—Diagram permitting the determination of the coördinates of the critical point and the point of inflection of the oxygen sag.

generalization, $L_a$ and $D_c$ are here expressed in terms of the dissolved oxygen saturation value $S$, *i.e.* the amount of oxygen that will saturate the

receiving water with oxygen. In fresh water at 20°C., for example, $S = 9.2$ p.p.m., and at 25°C., $S = 8.4$ p.p.m.

The graphical solution of the sample calculations just given is as follows:

*a.* Read for the intersection of the vertical through the abscissal value of $\frac{D_a}{L_a} = 0.16$ with the curve marked $f = 2.4$, the ordinate $k_1 t_c = 0.193$, or $t_c = 1.93$ days.

*b.* For $k_1 t_c = 0.193$ and $\frac{L_a}{fS} = \frac{20.0}{2.4 \times 9.2} = 0.91$, find $\frac{D_c}{S} = 0.58$, or $D_c = 0.58 \times 9.2 = 5.3$ p.p.m.

*c.* For $\frac{D_a}{L_a} = 0$ and $f = 2.4$, read $k_1(t_i - t_c) = 0.272$, or $t_i = 2.72 + 1.93 = 4.65$ days.

*d.* For $k_1(t_i - t_c) = 0.272$ and $\frac{f+1}{f}\frac{D_c}{S} = \frac{3.4}{2.4} \times \frac{5.3}{9.2} = 0.82$, read $\frac{D_i}{S} = 0.44$, or $D_i = 0.44 \times 9.2 = 4.0$ p.p.m.

*Limitations of Equations and Diagram.*—The equations and the diagram representing them cannot be solved directly for the general case of finding the permissible loading, $L_a$, of a receiving water. A first estimate must be made of $L_a$ and the answer obtained by successive approximation or graphical interpolation. Figure 2, however, does indicate the possible range of $L_a$ for a given value of $f$ and $D_c$. As will be shown, further analysis of the oxygen sag curve yields a fairly satisfactory method for solving this important problem.

## Maximum Loading of Receiving Waters

Inspection of equations (2c) and (2d) or (2f) shows that the pollutional load that can be placed upon a stream, or other body of water, is determined (1) by the value of the self-purification constant, $f$; (2) by the magnitude of the critical deficit, $D_c$; and (3) by the relative value of the initial deficit, $D_a$.

*The Self-purification Constant, f.*—Present information indicates the following approximate values for the self-purification constant, $f$, at 20° C. (*i.e.* $f_{20}$):

| Nature of Receiving Water | Value of $f_{20}$ |
|---|---|
| *a.* Small ponds and backwaters | 0.5 to 1.0 |
| *b.* Sluggish streams and large lakes or impounding reservoirs | 1.0 to 1.5 |
| *c.* Large streams of low velocity | 1.5 to 2.0 |
| *d.* Large streams of normal velocity | 2.0 to 3.0 |
| *e.* Swift streams | 3.0 to 5.0 |
| *f.* Rapids and waterfalls | above 5.0 |

Obviously this classification of waters is not sharply defined. Each class merges into its adjacent class, and there is appreciable variation within the

general types of waters that are here only roughly described in words. At temperatures ($T$) other than 20° C., the self-purification constant $f_T$ bears the following relation to $f_{20}$:

$$f_T = f_{20} \times 0.970^{(T-20)} \tag{4c}$$

This follows from the well-known equations of Streeter, Phelps and Theriault:

$$k_{1(T)} = k_{1(20)} \times 1.047^{(T-20)} \quad \text{and} \quad k_{2(T)} = k_{2(20)} \times 1.0159^{(T-20)}$$

The magnitude of $f$, therefore, decreases with rising temperatures and increases with falling temperatures by about 3 per cent compounded per degree Centigrade. The relative magnitude of $f$ at temperatures other than 20° C. may be read from the following schedule:

| Temperature —° C. | 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| Relative value of $f$ | 1.58 | 1.35 | 1.16 | 1.00 | 0.859 | 0.737 |

A wider use of the concepts of the oxygen sag should lead in time to a closer definition of the magnitude of $f$ for different types of receiving waters.

*The Critical Deficit, $D_c$.*—If septic conditions are to be avoided the upper limit of the critical deficit is the dissolved-oxygen saturation value, $S$, of the receiving water, *i.e.* 9.2 p.p.m. at 20° C. and 8.4 p.p.m. at 25° C. in fresh water. For the maintenance of normal fish life the dissolved-oxygen content apparently must not fall below 3 to 5 p.p.m., corresponding to an allowable critical deficit at 20° C. of 6.2 to 4.2 p.p.m., and at 25° C. of 5.4 to 3.4 p.p.m.

*The Initial Deficit, $D_a$.*—For given values of $f$ and $D_c$, the maximum loading of receiving waters is circumscribed by the initial deficit, $D_a$. This deficit has two limiting values: (1) zero deficit when the stream is fully saturated with oxygen at the point of pollution, and (2) a deficit equal to the critical deficit. These two boundary conditions are illustrated in Fig. 3 and define the upper and lower limits of maximum loading of receiving waters. All permissible maximum loadings must lie between the two boundary values.

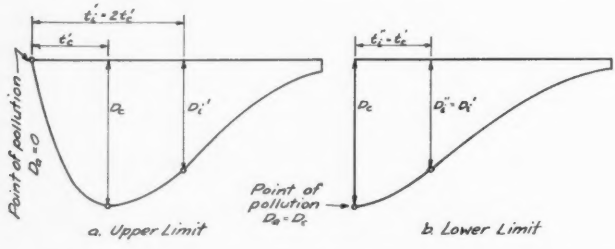


FIG. 3.—Boundary conditions for maximum loading of receiving waters in relation to the oxygen sag.

These boundary restrictions establish certain simple mathematical relationships for the maximum loading of receiving waters and for the coördinates of the characteristic points of the dissolved oxygen sag.

5. *Upper Limit of Maximum Loading.*—In the most favorable circumstances, the receiving water is fully saturated with oxygen at the point of pollution and $D_a = 0$ (Fig. 3*a*). If a certain oxygen concentration equal to or greater than zero is to be maintained, the maximum allowable oxygen deficit equals the critical deficit $D_c$. The allowable loading, $L_a'$, and the coördinates $t_c'$ and $t_i'$ and $D_i'$ are then defined by the following equations:

For $D_a = 0$, equation (2c) becomes:

$$k_1 t_c' = \frac{1}{f-1} \log f \tag{5a}$$

and for a value of $f = 1$,

$$k_1 t_c' = 0.4343 \tag{5a'}$$

To find the allowable loading, $L_a'$, equations (2d) and (2f) may be transformed to read:

$$\frac{L_a'}{D_c} = f \cdot 10^{k_1 t_c'} \tag{5b}$$

or

$$\log \frac{L_a'}{D_c} = \log f + k_1 t_c' \tag{5c}$$

Also

$$\log \frac{L_a'}{D_c} = \frac{f}{f-1} \log f = f k_1 t_c' \tag{5c'}$$

From equations (4a) and (5a):

$$k_1(t_i' - t_c') = \frac{1}{f-1} \log f = k_1 t_c' \tag{5d}$$

or

$$t_i' = 2t_c' \tag{5e}$$

From equations (4b) and (5d):

$$\frac{D_i'}{D_c} = \frac{f+1}{f} \cdot 10^{-k_1 t_c'} \tag{5f}$$

From equation (5b):

$$\frac{D_i'}{D_c} = (f+1) \frac{D_c}{L_a'} \tag{5g}$$

6. *Lower Limit of Maximum Loading.*—In the most unfavorable circumstances, the dissolved-oxygen deficit of the receiving water at the point of pollution reaches a value equal to the allowable or critical deficit and $D_a = D_c$ (Fig. 3*b*). The allowable loading, $L_a''$, and the coördinates $t_c''$ and $t_i''$ and $D_i''$ are then given by the following equations:

To meet the condition that $D_a = D_c$:

$$t_c'' = 0 \tag{6a}$$

The allowable loading, $L_a''$, equations (2d) and (6a) state, is:

$$\frac{L_a''}{D_c} = f \tag{6b}$$

From equations (4a), (6a) and (5a), it follows that:

$$t_i'' = \frac{1}{f-1} \cdot \frac{\log f}{k_1} = t_c' \tag{6c}$$

From equations (4b), (6a) and (6c):

$$\frac{D_i''}{D_c} = \frac{f+1}{f} \cdot 10^{-k_1 t_c'} \tag{6d}$$

From equation (5f):

$$\frac{D_i''}{D_c} = \frac{D_i'}{D_c} \qquad \text{or} \qquad D_i'' = D_i' \tag{6e}$$

The ratio of the upper to the lower limit of maximum loading, in logarithmic form, therefore equals

$$\log \frac{L_a'}{L_a''} = \frac{1}{f-1} \log f = k_1 t_c' \tag{6f}$$

*Solution and Graphical Presentation of Boundary Equations.*—It will be noted that the allowable loading and the coördinates of the characteristic points in the oxygen sag may be generalized in terms of the critical deficit $D_c$ and that they then become simple functions of the self-purification coefficient $f$. Hence their values, for various magnitudes of $f$, may be expressed in simple tabular or graphical form, as shown in Table I and in Fig. 4.

Certain features of the boundary equations should be emphasized, because their inherent simplicity establishes certain concepts of the reaction of receiving waters to pollution that are easily carried in mind.

1. The lower limit of allowable loading of receiving waters equals $f$ times the allowable dissolved-oxygen deficit.

2. The upper limit of allowable loading is about twice the lower limit in normal streams, increasing for lower values of $f$ and decreasing for higher ones.

3. The inflection deficit is close to three-fourths of the allowable, or critical, deficit in almost all classes of waters.

4. For the upper limit of loading the critical time, in normal streams, is about three days at high summer temperatures, and the inflection time about six days (*i.e.* twice as long). The time factor increases for lower values of $f$ and decreases for higher ones.

5. For the lower limit of loading the critical time is zero and the inflection time in normal streams at high summer temperatures is about three days, increasing for lower values of $f$ and decreasing for higher ones.

*Sample Calculations.*—The use of the boundary equations and of Table I and Fig. 4 is illustrated in the following sample calculations:

*Given* $f = 2.4$ ($k_2 = 0.24$ and $k_1 = 0.10$ at 20° C.); $S = 9.2$ p.p.m.; and the maintenance of a minimum dissolved-oxygen content of 4.0 p.p.m., *i.e.* $D_c = 9.2 - 4.0 = 5.2$ p.p.m.

*Find* from the equations, the table and the diagram:

TABLE I.—*Maximum Loading of Receiving Waters and Coördinates of Characteristic Points of Oxygen Sag under Conditions of Maximum Loading*

| Class of Receiving Water | Self-Purification Constant, $f$, or Deoxygenation-Reaeration Ratio $k_2/k_1$ | Maximum Loading | | Critical Time $k_1t_c'$ for Upper Limit and Inflection Time $k_1t_i''$ for Lower Limit | Inflection Time $k_1t_i'$ for Upper Limit | Inflection Deficit $D_i'/D_c$ and $D_i''/D_c$ |
|---|---|---|---|---|---|---|
| | | Lower Limit $L_a''/D_c$ | Upper Limit $L_a'/D_c$ | | | |
| (0) | (1) | (2) | (3) | (4) | (5) | (6) |
| Small Ponds and Backwaters | 0.2 | 0.2 | 1.50 | 0.874 | 1.75 | 0.80 |
| | 0.4 | 0.4 | 1.84 | 0.663 | 1.33 | 0.76 |
| | 0.6 | 0.6 | 2.15 | 0.554 | 1.11 | 0.74 |
| | 0.8 | 0.8 | 2.44 | 0.484 | 0.97 | 0.74 |
| Sluggish Streams and Large Lakes | 1.0 | 1.0 | 2.72 | 0.434 | 0.87 | 0.74 |
| | 1.2 | 1.2 | 2.99 | 0.396 | 0.79 | 0.74 |
| | 1.4 | 1.4 | 3.24 | 0.365 | 0.73 | 0.74 |
| Large Slow Streams | 1.6 | 1.6 | 3.50 | 0.340 | 0.68 | 0.74 |
| | 1.8 | 1.8 | 3.75 | 0.319 | 0.64 | 0.75 |
| | 2.0 | 2.0 | 4.00 | 0.301 | 0.60 | 0.75 |
| Large Normal Streams | 2.2 | 2.2 | 4.26 | 0.286 | 0.57 | 0.75 |
| | 2.4 | 2.4 | 4.49 | 0.272 | 0.54 | 0.76 |
| | 2.6 | 2.6 | 4.72 | 0.259 | 0.52 | 0.76 |
| | 2.8 | 2.8 | 4.96 | 0.248 | 0.50 | 0.77 |
| Swift Streams | 3.0 | 3.0 | 5.20 | 0.239 | 0.48 | 0.77 |
| | 3.5 | 3.5 | 5.78 | 0.218 | 0.44 | 0.78 |
| | 4.0 | 4.0 | 6.36 | 0.201 | 0.40 | 0.79 |
| | 4.5 | 4.5 | 6.92 | 0.187 | 0.37 | 0.79 |
| | 5.0 | 5.0 | 7.48 | 0.175 | 0.35 | 0.80 |
| Rapids and Waterfalls | 6.0 | 6.0 | 8.63 | 0.158 | 0.32 | 0.81 |
| | 8.0 | 8.0 | 10.8 | 0.129 | 0.26 | 0.84 |
| | 10.0 | 10.0 | 12.9 | 0.111 | 0.22 | 0.85 |
| | 15.0 | 15.0 | 18.2 | 0.084 | 0.17 | 0.88 |
| | 20.0 | 20.0 | 23.4 | 0.068 | 0.14 | 0.90 |
| | 25.0 | 25.0 | 25.6 | 0.058 | 0.12 | 0.91 |

*Maximum Loading*

| | *Upper Limit* | *Lower Limit* |
|---|---|---|
| *a.* | $k_1t_c' = \dfrac{1}{f-1}\log f = \dfrac{\log 2.4}{1.4} = 0.272$ | ——— |
| | $t_c' = 2.72$ days | $t_c'' = 0$ days |
| *b.* | $\log \dfrac{L_a'}{D_c} = fk_1t_c' = 2.4 \times 0.272 = 0.652$ | ——— |
| | $\dfrac{L_a'}{D_c} = 4.49$ | $\dfrac{L_a''}{D_c} = f = 2.4$ |
| | $L_a' = 4.49 \times 5.2 = 23.4$ p.p.m. | $L_a'' = 2.4 \times 5.2 = 12.5$ p.p.m. |

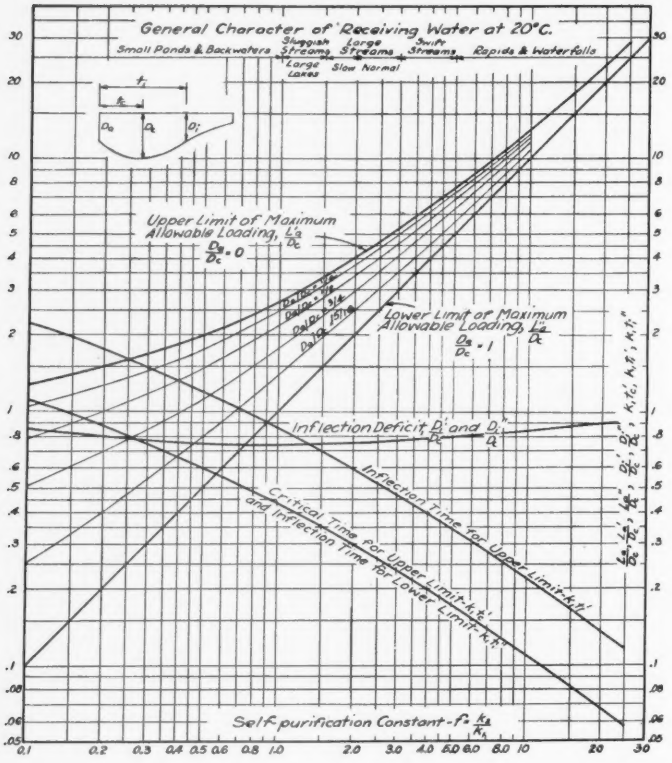
General Character of Receiving Water at 20°C.
Small Ponds & Backwaters
Sluggish Streams
Large Streams
Swift Streams
Rapids & Waterfalls
Large Lakes
Slow
Normal
Upper Limit of Maximum Allowable Loading, La/Dc
Da/Dc = 0
Da/Dc = 1/4
Da/Dc = 1/2
Da/Dc = 3/4
Da/Dc = 1/1
Lower Limit of Maximum Allowable Loading, La/Dc
Da/Dc = 1
Inflection Deficit Di'/Dc and Di''/Dc
Inflection Time for Upper Limit kt'
Critical Time for Upper Limit kt' and Inflection Time for Lower Limit kt''
Self-purification Constant - f = Ka/Kr

FIG. 4.—Diagram for the determination of the maximum allowable loading of receiving waters and the associated coördinates of the critical point and point of inflection of the oxygen sag.

*c.* $t_i' = 2t_c' = 2 \times 2.72 = 5.44$ days $\qquad t_i'' = t_c' = 2.72$ days

*d.* $\dfrac{D_i'}{D_c} = (f + 1)\dfrac{D_c}{L_a'} = \dfrac{3.4}{4.49} = 0.757$ $\qquad$ ———

$D_i' = 0.757 \times 5.2 = 3.94$ p.p.m. $\qquad D_i'' = D_i' = 3.94$ p.p.m.

*e.* $\log \dfrac{L_a'}{L_a''} = k_1 t_c' = 0.272$ and

$$\frac{L_a'}{L_a''} = 1.87$$

The allowable loading of the stream, therefore, lies between 12.5 and 23.4 p.p.m. for initial deficits of 5.2 and 0.0 p.p.m., respectively.

If the initial deficit is neither 5.2 nor 0 p.p.m., but 2.0 p.p.m., the allowable loading is neither 12.5 nor 23.4 p.p.m. but must lie somewhere between these boundary values. The proper magnitude may be ascertained with the aid of Fig. 4, as follows:

*a.* Read for $\frac{D_a}{D_c} = \frac{2.0}{5.2} = 0.385$ and $f = 2.4$:

$$\frac{L_a}{D_c} = 4.1 \qquad \text{or} \qquad L_a = 4.1 \times 5.2 = 21.3 \text{ p.p.m.}$$

*b.* Read in Fig. 2 for $\frac{D_a}{L_a} = \frac{2}{21.3} = 0.094$ and $f = 2.4$:

$$k_1 t_c = 0.227 \qquad \text{or} \qquad t_c = 2.27 \text{ days.}$$

The curves between the upper and lower limits of maximum leading stem from equations (2c) and (2d) and were calculated by the author's colleague, Dr. H. A. Thomas Jr., by approximating the combined equation by a Taylor series.

## Dilution Requirements

Engineers have long been familiar with the converse of allowable loading of streams, namely required dilution. This parameter is commonly expressed as required stream flow, $Q$, in cubic feet per second per 1000 population and varies, according to different authorities, under different conditions of initial deficit and character of stream flow, from a low value of 2.5 c.f.s. up to a high value of 10 c.f.s. per 1000 population. The values assigned to required dilution were based, in general, on observations of the condition of streams receiving municipal sewage from combined systems. The biochemical oxygen demand of the daily pollutional load, therefore, may be estimated at 0.17 lb. per capita at 20° C. in 5 days. The corresponding first-stage demand, $L_c$, is 0.25 lb. at 20° C. and 0.275 lb. at 25° C., close to the maximum summer temperature of most streams in temperate climates. Industrial wastes, in significant amounts, may be allowed for by expressing their B.O.D. in terms of their population equivalent. The per capita values of $L_{c(20)} = 0.25$ lb. and $L_{c(25)} = 0.275$ lb. are equivalent respectively to $L_{c(20)} = 46.4$ p.p.m. and $L_{c(25)} = 51.0$ p.p.m. for each cubic foot per second of required dilution per 1000 population. For temperatures other than 20° C., $L_{c(T)} = 46.4[1 + 0.02(T - 20)]$ as shown by Streeter, Phelps and Theriault.

*Formulation of Dilution Requirements.*—The boundary equations for the allowable maximum loading of receiving waters are readily translated into equations for the required dilution, $Q$.

7. *Required Dilution.*—Since $Q = L_c/L_a$, the lower limit of required dilution, $Q'$, is given by substituting for $L_a$ in equation (5c) the value $L_a = \frac{L_c}{Q}$ and solving for $Q$, or:

$$\log Q' = \log \frac{L_c}{D_c} - \frac{f}{f-1} \log f \tag{7a}$$

For $f = 1$,

$$\log Q' = \log \frac{L_c}{D_c} - 0.4343 \tag{7a'}$$

Similarly, the upper limit of required dilution, $Q''$, follows from equation (6b):

$$Q'' = \frac{L_c}{fD_c} \qquad \text{or} \qquad \log Q'' = \log \frac{L_c}{D_c} - \log f \tag{7b}$$

The ratio of the upper to the lower limit of required dilution in logarithmic form, therefore, equals:

$$\log \frac{Q''}{Q'} = \frac{1}{f-1} \log f = \log \frac{L_a'}{L_a''} \tag{7c}$$

For $f = 1$,

$$\log \frac{Q''}{Q'} = 0.4343 \tag{7c'}$$

The values of $Q'$ and $Q''$ may be obtained from columns (2) and (3) of Table I or from the lines of maximum loading, in Fig. 4 since:

$$\frac{L_a'}{D_c} = \frac{L_c}{Q'D_c} \qquad \text{and} \qquad \frac{L_a''}{D_c} = \frac{L_c}{Q''D_c} \tag{7d}$$

*Sample Calculations.*—The use of these equations in connection with Table I or Fig. 4 may be exemplified as follows:

*Given* $f = 2.4$, $L_c = 46.4$ p.p.m., a required oxygen residual of 4 p.p.m. and a temperature of 20° C., *i.e.* $D_c = 9.2 - 4.0 = 5.2$ p.p.m.

*Find*, for $f = 2.4$, in Fig. 4 or Table I:

*a.* $\dfrac{L_a'}{D_c} = 4.49$ and $\dfrac{L_a''}{D_c} = 2.4$

*b.* From equation (7d):

$$Q' = \frac{L_cD_c}{D_cL_a'} = \frac{46.4}{5.2 \times 4.49} = 2.0 \text{ c.f.s. per 1000 population}$$

and

$$Q'' = \frac{L_cD_c}{D_cL_a''} = \frac{46.4}{5.2 \times 2.4} = 3.7 \text{ c.f.s. per 1000 population}$$

If the water temperature were 25° C., instead of 20° C., the following changes would be effected:

(1) $f = 2.4 \times 0.97^{(25-20)} = 2.4 \times 0.86 = 2.1$

(2) $L_c = 46.4[1 + 0.02(25 - 20)] = 51.0$ p.p.m.

(3) $D_c = 8.4 - 4.0 = 4.4$ p.p.m.

For these conditions, *find*, for $f = 2.1$, in Fig. 4 or Table I:

(*a*) $\dfrac{L_a'}{D_c} = 4.13$ and $\dfrac{L_a''}{D_c} = 2.1$

(*b*) From equation (7d):

$$Q' = \frac{51.0}{4.4 \times 4.13} = 2.8 \text{ c.f.s. per 1000 population}$$

and

$$Q'' = \frac{51.0}{4.4 \times 2.1} = 5.5 \text{ c.f.s. per 1000 population}$$

A rise in temperature from 20 to 25° C., therefore, increases the lower limit of required dilution by 40 per cent and the upper limit by almost 50 per cent.

*Correlation between Required Dilution and Allowable Loading.*—It is of some interest, in connection with the question of required dilution, to work back from the outside values of 2.5 and 10 c.f.s. per 1000 population with a view to ascertaining the type of stream, as characterized by $f$, that would take care of the pollutional load imposed upon it.

Calculations made with the aid of equation (7b) and Fig. 4 show the values given in Table II for:

TABLE II.—*Values of the Self-Purification Constant, f, Corresponding to Certain Required Dilutions*

(Calculations are based upon combined sewage and a temperature of 25° C. The values of $f$ are reduced to a base temperature of 20° C.)

| Oxygen Conditions | | Dilution—c.f.s. per 1000 Population | | |
|---|---|---|---|---|
| Residual Oxygen P.P.M. | Initial Deficit | 10.0 | 4.0 | 2.5 |
| 0.0 | Zero | $f < 0.1$ | $f = 0.3$ | $f = 1.1$ |
| 4.0 | Zero | $f = 0.1$ | $f = 1.5$ | $f = 3.2$ |
| 0.0 | Critical | $f = 0.7$ | $f = 1.8$ | $f = 2.8$ |
| 4.0 | Critical | $f = 1.4$ | $f = 3.4$ | $f = 5.4$ |
| Class of Stream—Range | | Backwater to sluggish | Backwater to swift | Sluggish to rapids |
| —Average | | Sluggish | Large with slow velocity | Swift |

*a.* Hazen's estimate of 1898 that a sluggish stream, already partially depleted of oxygen at the point of sewage discharge may require a runoff of as much as 10 c.f.s. per 1000 population;

*b.* Stearns' estimate of 1890 that the lowest required dilution of normal streams is 2.5 c.f.s. per 1000 population; and

*c.* the common value of 4 c.f.s. per 1000 population.

It is evident that the modern mathematical formulation of the oxygen sag is in full agreement with the engineering judgment of early investigators and that the values by suggested Hering, Stearns, Hazen and Goodnough may well continue to serve as general measures of required dilution in those classes of streams for which the values were first considered applicable about half a century ago.

## NON-MATHEMATICAL GENERALIZATION OF ALLOWABLE LOADING

The calculus involved in this analysis of the Streeter and Phelps dissolved-oxygen sag is of a simple order. Nevertheless, the author is not

sufficient of a mathematical snob to leave, with this figurative wave of the hand, those of his professional associates who, on principle, shy away from mathematics. It is indeed an easy matter to develop, by means of the various formulations, tables and graphs presented in this paper, a generalized table that will make some of the most interesting results of the analysis available to all. Such is the purpose of Table III. But a warning is

TABLE III.—*Allowable B.O.D. Load-factor, F, and Associated Critical Time, $t_c$, of Receiving Waters*

Allowable 5-day, 20° C. B.O.D. ($L_A$) = Load-factor ($F$) × Critical deficit ($D_c$). Critical deficit ($D_c$) = Dissolved-oxygen saturation value ($S$) − Lowest allowable dissolved-oxygen content.

| Class of Receiving Water | Load-Factor, $F$ | | | | | |
|---|---|---|---|---|---|---|
| | Lower Limit * | | | Upper Limit † | | |
| | 15° C. | 20° C. | 25° C. | 15° C. | 20° C. | 25° C. |
| 1. Small ponds and backwaters | 0.6 | 0.5 | 0.4 | 2.1 | 1.6 | 1.3 |
| 2. Sluggish streams and large lakes and reservoirs | 1.1 | 0.9 | 0.7 | 2.7 | 2.1 | 1.6 |
| 3. Large slow streams | 1.6 | 1.2 | 0.9 | 3.2 | 2.5 | 2.0 |
| 4. Large normal streams | 2.2 | 1.7 | 1.3 | 4.0 | 3.2 | 2.5 |
| 5. Swift streams | 3.5 | 2.7 | 2.1 | 5.4 | 4.3 | 3.3 |
| 6. Rapids ‡ | 22 | 17 | 13 | 25 | 20 | 16 |
| | Critical Time, $t_c$ § | | | | | |
| 1. Small ponds and backwaters | 0 | 0 | 0 | 5.9 | 5.0 | 4.3 |
| 2. Sluggish streams and large lakes and reservoirs | 0 | 0 | 0 | 4.5 | 3.9 | 3.3 |
| 3. Large slow streams | 0 | 0 | 0 | 3.8 | 3.2 | 2.8 |
| 4. Large normal streams | 0 | 0 | 0 | 3.0 | 2.6 | 2.3 |
| 5. Swift streams | 0 | 0 | 0 | 2.3 | 2.0 | 1.8 |
| 6. Rapids ‡ | 0 | 0 | 0 | 0.6 | 0.6 | 0.5 |

* When the dissolved-oxygen content of the receiving water immediately below the point of sewage discharge is at the lowest allowable value, *i.e.* when the dissolved-oxygen deficit is at its maximum or critical value, $D_c$.

† When the dissolved-oxygen content of the receiving water immediately below the point of sewage discharge is at the saturation value of 10.2, 9.2 or 8.4 p.p.m. at 15, 20 or 25° C. respectively in fresh water.

‡ Varying greatly with the nature of the rapids.

§ Time of flow between point of sewage discharge and critical point (point of maximum, or critical, deficit or of lowest allowable dissolved-oxygen content).

attached. The figures listed are based on the author's best estimate of the self-purification constant, $f$, for different types of receiving waters; also they are restricted by the fact that an average value has been chosen to represent a range of magnitudes.

An example will illustrate the use of Table III.

(*a*) *What is the maximum allowable 5-day 20° C. B.O.D. of the water in a large slow stream immediately below the point of sewage discharge, if the water temperature is 25° C. and the lowest allowable dissolved-oxygen concentration of the stream is to be 5.0 p.p.m.?*

From Table III, the load-factor $F$ = 0.9 (lower limit) to 2.0 (upper limit); also the critical deficit $D_c$ = 8.4 (saturation value) − 5.0 (lowest

allowable value) = 3.4 p.p.m. Hence the maximum allowable 5-day, 20° C. B.O.D., $L_A = FD_c$, lies between $0.9 \times 3.4 = 3.1$ p.p.m. and $2.0 \times 3.4 = 6.8$ p.p.m.

(*b*) *If the 5-day, 20° C. B.O.D. of the sewage discharged is 180 p.p.m., what is the required dilution in river water?*

The required dilution lies between $\frac{180}{3.1} = 58.1$ fold and $\frac{180}{6.8} = 26.5$ fold.

If the stream water itself has a B.O.D. when it arrives at the point of sewage discharge, this value must be subtracted from the allowable values before making the division.

(*c*) *If the per capita flow of sewage is 80 g.p.d., what is the required stream flow in cubic feet per second per 1000 population?*

Since $80 \times 1000$ g.p.d. = 0.124 c.f.s. per 1000 population, the required stream flow lies between $(58.1 - 1) \times 0.124 = 7.1$ and $(26.5 - 1) \times 0.124 = 3.2$ c.f.s. per 1000 population.

(*d*) *How far away from the point of sewage discharge will the lowest dissolved-oxygen concentration be experienced?*

From Table III, the critical time, $t_c$, lies between 0 and 2.8 days. The distance in miles, therefore, equals the stream velocity in miles per day times the critical time. For the lower limit of loading the distance is always zero.

*Limitations of Discussion.*—It has been assumed throughout this paper that the sewage matters reaching the receiving water will remain in suspension and that they will decompose aerobically in accordance with the normal law of biochemical oxidation. If some of the solids settle to the bottom of the receiving water, the conditions of deoxygenation and reaeration will be changed. There are various ways of taking this phase of the problem of sewage disposal by dilution into account. None of them is very satisfactory, because the required knowledge of existing conditions is seldom complete enough to permit of rigid mathematical interpretation. The information included in this paper applies only to receiving waters into which settled sewage is discharged or which are otherwise sufficiently swift to prevent the deposition of decomposable solids.

# ACTIVATED SLUDGE OXIDATIONS

## II. A COMPARISON OF OXYGEN UTILIZATION BY ACTIVATED SLUDGES OBTAINED FROM FOUR WISCONSIN MUNICIPALITIES

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Activated sludge, until recently, has been considered by many workers to be a definite entity. This concept has led to a quite uniform design of activated sludge plants with provisions made mainly for variations in sewage strength as measured by the B.O.D. The recent work of several investigators has indicated that activated sludges from separate sources might have widely different characteristics, and this paper is presented to support this contention. Recognition of this variable alone will be of little value to the designing engineer unless the causative factors responsible for such changes are determined. The work of Heukelekian and Ingols (1), in which they compared several activated sludges on the basis of carbon dioxide production, indicated that the rate and manner of oxidation probably varied greatly with the different sludges and sewages used. Bloodgood (2) has shown that the activity of the activated sludge at the Indianapolis plant can vary widely even in as short a period as two weeks. Ruchhoft, McNamee, and Butterfield (3) have reported that the biochemical character and activity of sludges are important in determining the amount of oxygen used to stabilize equivalent amounts of food material. They also have reported that the amount of oxygen used by activated sludges in stabilizing sewages may vary from 40 to over 100 per cent of the 5-day B.O.D. depending upon the extent of nitrification.

While investigating the rate of oxygen utilization by activated sludge-sewage mixtures with the aid of the "Odeeometer" and the chemical method (4) during 1936–7, it was found that the rate curves on sludge-sewage mixtures differed widely for the different plants visited but were quite consistent over a short period for a given plant. This was considered as due possibly to the difference in character of the sewage as well as the activated sludge.

With the development of the Oxy-Utilometer, which has been previously described (5), (6), it became possible for one person carrying on independent research to compare, simultaneously under identical conditions, sludges and sewages from different sources.

### Methods and Sources of Materials

All investigations involving the oxygen utilization by various activated sludges were made using four Oxy-Utilometer units operated under controlled temperature conditions.

Activated sludge A was collected on January 12, 1938, and was kept

under laboratory condition with bi-daily feeding on Sewage A for 60 days prior to and during the course of these experiments. This sludge was used as a common means of comparison of the other sludges since in all runs it was used as a control or reference sludge.

Activated sludges and sewages were collected between the hours of 8 and 10 A.M. at three other activated sludge plants in Wisconsin and transported by auto to the laboratory. The maximum time elapsing between the collection of the samples and the start of the experimental run was about three hours. As soon as the activated sludges were brought to the laboratory they were aerated vigorously until all necessary preparations prior to the start of the run had been made, usually about 30 minutes. Just prior to charging the instruments the sludges and sewages were adjusted to the temperature at which the run was to be made. Two of the instruments (for example No. 1 and No. 2) were charged with equal portions of Sludge A and the other two (No. 3 and No. 4) were charged with the other sludge being studied on that day (as example Sludge C). Sewage A was then added to one of the instruments containing Sludge A and to one containing Sludge C. Sewage C was added to the other two instruments. In this manner each sludge was used to oxidize and stabilize a sewage to which it was accustomed and also a foreign sewage.

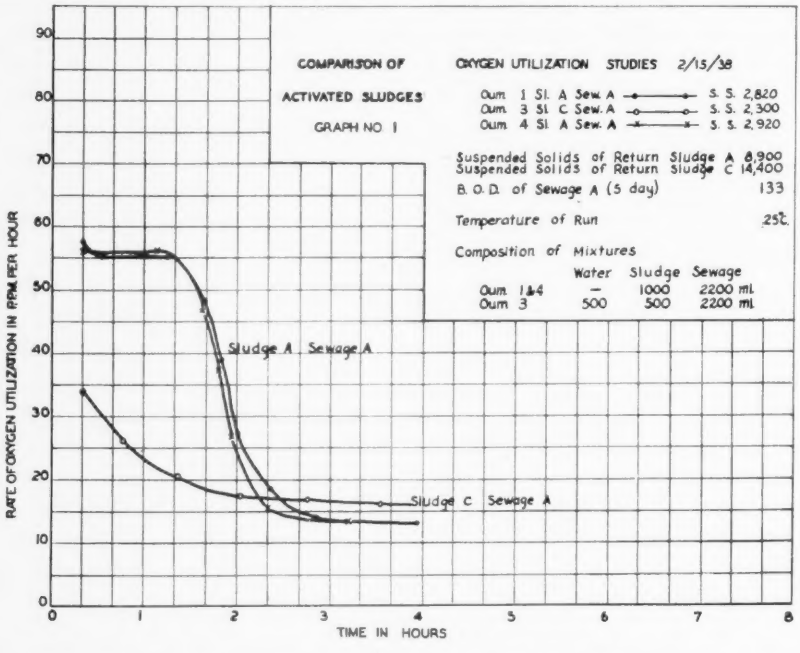
Base rates (sludge without sewage addition) of oxygen utilization by the activated sludges were obtained the next day after the samples were collected. The sludges were aerated during this twenty-four hour period without addition of food.

## Experimental Results

A preliminary run was made in which Sludge A and Sludge C were used to oxidize separate portions of Sewage A. In this particular run, two instruments, No. 1 and No. 4, were each charged with identical mixtures of Sludge A and Sewage A and instrument No. 3 was charged with Sludge C and Sewage A. The results of these runs are shown in Graph 1. The ability to duplicate results with the Oxy-Utilometers is shown by the similarity and closeness of the curves for instruments No. 1 and No. 4 which had identical charges of sludge and sewage. The oxygen utilization rate curves for Sludge A and Sludge C are, however, in marked contrast. The smaller amount of oxygen used by Sludge C indicates that such a sludge would favor much more economical plant operation provided comparable purification was obtained. The results of 5-day B.O.D. values obtained on the supernatants at the end of the run showed a 96.4 per cent reduction by Sludge A and 93.6 per cent reduction by Sludge C. This marked difference in oxygen utilization with comparable purification during a four hour aeration period gave the necessary impetus to the remainder of the investigations presented in this paper.

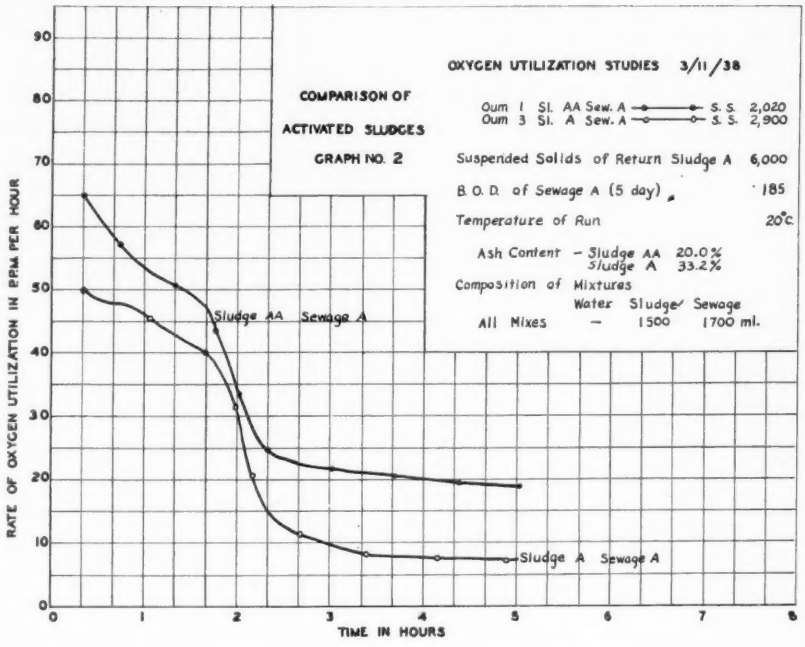
Since Sludge A had been fed under laboratory conditions for a period of about 60 days at the time it was decided to compare the various activated sludges, the first step in the comparative study was be-

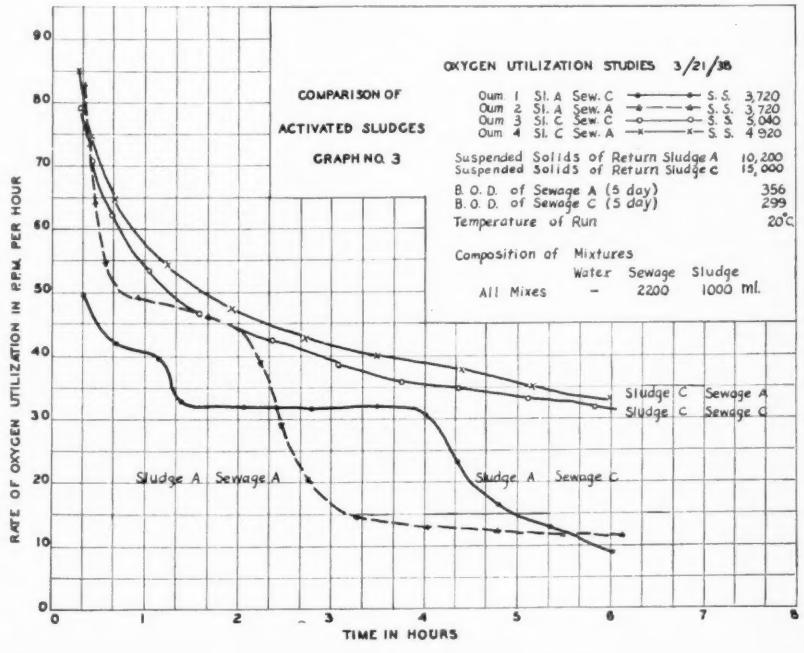
tween Sludge A and a new portion of Sludge AA, obtained from the same source. This study was made purposely to determine whether Sludge A had changed materially under its laboratory environment. Results of the comparison are given in Graph 2 and show that the character or type of the oxygen utilization curves is the same, but the curve produced by Sludge AA is of a much greater magnitude even though the amount of suspended solids used was less than for Sludge A. The much larger demand for oxygen by Sludge AA (about 2.5 times greater) at the end of 5 hours aeration is to be noted particularly. This fact, coupled with the greater overall magnitude of the curve given by Sludge AA, shows that it is impossible to compare the amount of work being accomplished in an activated sludge plant by considering only the concentration of suspended solids carried in the aerators.

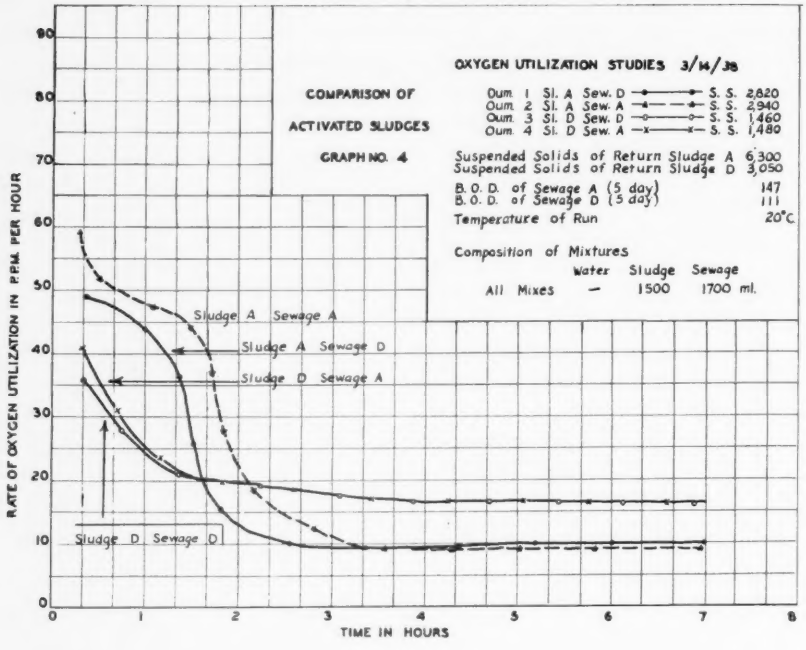


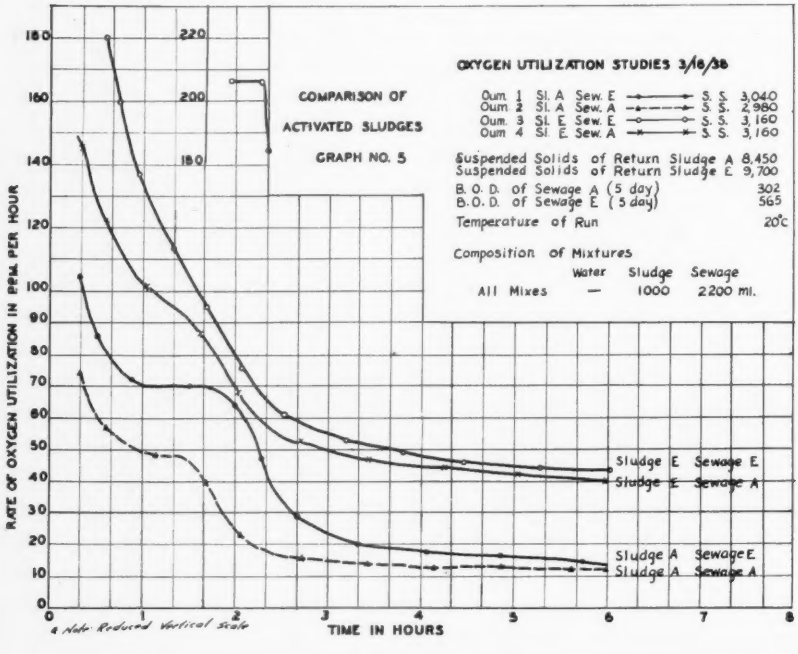

Sludges C, D, and E were compared, one at a time, with Sludge A. The results of these comparisons are shown in Graps 3, 4, and 5. It is of interest to note that Sludge A gave the same type of oxygen utilization rate curve regardless of the sewage being oxidized by it. When oxidizing Sewage C (Graph 3), the curve during the first 90 minutes differs considerably from that given by another portion of the same sludge which was oxidizing Sewage A. No explanation is offered for this anomaly.

The type of oxygen utilization curves produced by Sludges C, D, and E do not appear to differ in any radical manner when oxidizing the foreign Sewage A, from the curves given when each was oxidizing sew-


COMPARISON OF
ACTIVATED SLUDGES
GRAPH NO. 2
OXYGEN UTILIZATION STUDIES 3/11/38
Oum 1 Sl. AA Sew. A S. S. 2,020
Oum 3 Sl. A Sew. A S. S. 2,900
Suspended Solids of Return Sludge A 6,000
B. O. D. of Sewage A (5 day) 185
Temperature of Run 20°C
Ash Content – Sludge AA 20.0%
Sludge A 33.2%
Composition of Mixtures
Water Sludge Sewage
All Mixes – 1500 1700 ml.
Sludge AA Sewage A
Sludge A Sewage A
RATE OF OXYGEN UTILIZATION IN P.P.M. PER HOUR
TIME IN HOURS

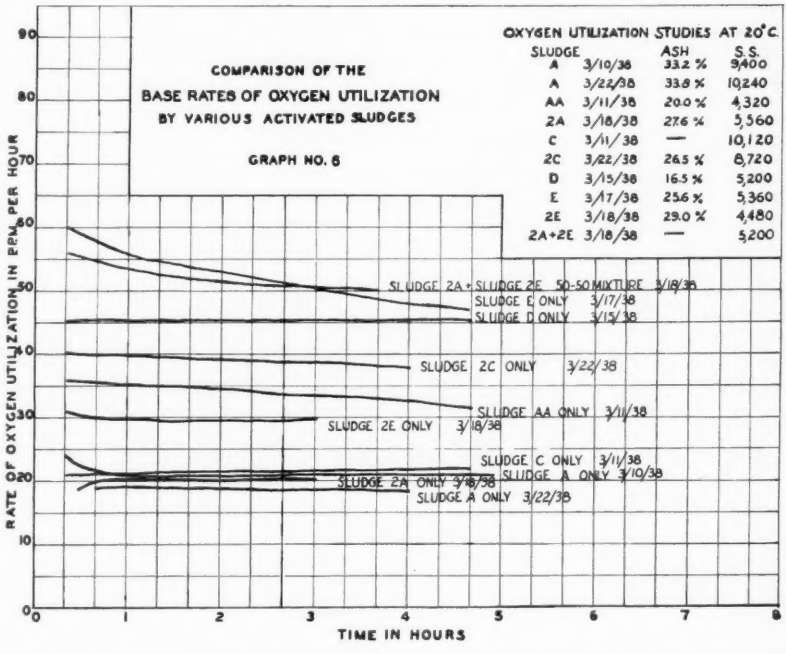

COMPARISON OF
ACTIVATED SLUDGES
GRAPH NO. 3
OXYGEN UTILIZATION STUDIES 3/21/38
Oum 1 Sl. A Sew. C S. S. 3,720
Oum 2 Sl. A Sew. A S. S. 3,720
Oum 3 Sl. C Sew. C S. S. 5,040
Oum 4 Sl. C Sew. A S. S. 4,920
Suspended Solids of Return Sludge A 10,200
Suspended Solids of Return Sludge C 15,000
B. O. D. of Sewage A (5 day) 356
B. O. D. of Sewage C (5 day) 299
Temperature of Run 20°C
Composition of Mixtures
Water Sewage Sludge
All Mixes – 2200 1000 ml.
Sludge C Sewage A
Sludge C Sewage C
Sludge A Sewage A
Sludge A Sewage C
RATE OF OXYGEN UTILIZATION IN P.P.M. PER HOUR
TIME IN HOURS


COMPARISON OF
ACTIVATED SLUDGES
GRAPH NO. 4
OXYGEN UTILIZATION STUDIES 3/14/38
Oum. 1 Sl. A Sew. D S. S. 2,820
Oum. 2 Sl. A Sew. A S. S. 2,940
Oum. 3 Sl. D Sew. D S. S. 1,460
Oum. 4 Sl. D Sew. A S. S. 1,480
Suspended Solids of Return Sludge A 6,300
Suspended Solids of Return Sludge D 3,050
B. O. D. of Sewage A (5 day) 147
B. O. D. of Sewage D (5 day) 111
Temperature of Run 20°C.
Composition of Mixtures
Water Sludge Sewage
All Mixes — 1500 1700 ml.
Sludge A Sewage A
Sludge A Sewage D
Sludge D Sewage A
Sludge D Sewage D
RATE OF OXYGEN UTILIZATION IN P.P.M. PER HOUR
TIME IN HOURS


COMPARISON OF
ACTIVATED SLUDGES
GRAPH NO. 5
OXYGEN UTILIZATION STUDIES 3/16/38
Oum. 1 Sl. A Sew. E S. S. 3,040
Oum. 2 Sl. A Sew. A S. S. 2,980
Oum. 3 Sl. E Sew. E S. S. 3,160
Oum. 4 Sl. E Sew. A S. S. 3,160
Suspended Solids of Return Sludge A 8,450
Suspended Solids of Return Sludge E 9,700
B. O. D. of Sewage A (5 day) 302
B. O. D. of Sewage E (5 day) 565
Temperature of Run 20°C
Composition of Mixtures
Water Sludge Sewage
All Mixes — 1000 2200 ml.
Sludge E Sewage E
Sludge E Sewage A
Sludge A Sewage E
Sludge A Sewage A
RATE OF OXYGEN UTILIZATION IN P.P.M. PER HOUR
TIME IN HOURS
4 Note Reduced Vertical Scale

age to which it was accustomed. This correlates with the behavior of Sludge A and indicates that the sewage is probably not an important immediate factor in determining the type of curve produced provided the sewage constitutes a well-balanced diet with respect to carbonaceous and nitrogenous materials.

Base rates of oxygen utilization by activated sludges alone, obtained after 24 hours of aeration without feeding, were found to hold fairly constant in most cases during the course of a three or four hour run. All results are shown on Graph 6. In each case the letter of the sludge denotes the source while a numeral preceding the letter denotes a second run made at a later date, in most cases with a new supply of sludge




from that source. Outstanding among the base rate curves is that given by Sludge E. The run made on 3/17/38 showed a rapidly decreasing oxygen usage which dropped from a value of 60 at the beginning of the run to 47 about 5 hours later. Because of this characteristic, a base rate run on this sludge was made again at the end of 48 hours aeration without feeding. This sludge is denoted by 2E and shows a much more stable sludge since the rate does not change materially during the course of the run. It should be mentioned that the ash content of this sludge increased from 23.4 per cent as collected at the plant to 25.6 per cent after 24 hours aeration without feeding and at the end of 48 hours aeration the ash content had increased to 29.0 per cent.

A mixture of Sludges 2A and 2E (50–50) was studied in one of the instruments at the same time that base rates were determined for each

separately. Instead of the mixture giving a rate which was an average of that for Sludges 2A and 2E, it gave an unexpectedly high rate (Graph 6). This phenomenon has since been verified on new portions of these same sludges and indicates that the end-products of oxidation of one sludge are not necessarily the end-products of the other, and that the products of one sludge may become food for the other. This experiment was originally tried because of the marked difference in physical and microscopic appearances of Sludges 2A and 2E.

An attempt has been made to correlate the base rates of oxygen utilization by activated sludges on the basis of the suspended solids concentrations in Table I. Although the sludges are arranged in order

TABLE I.—*Comparison of Base Rates * of Oxygen Utilization of Activated Sludges at 20° C. on the Basis of Suspended Solids Concentration*

| Sludge | S.S. Conc. in P.p.m. | Base Rate in P.p.m. of $O_2$ per Hour | Mg. of $O_2$ per Hour per Gram of Sludge |
|---|---|---|---|
| AA | 4,320 | 34 | 7.9 |
| 2E | 4,480 | 30 | 6.7 |
| D | 5,200 | 45.5 | 8.7 |
| E | 5,360 | 52 | 9.8 |
| 2A | 5,560 | 20 | 3.6 |
| 2C | 8,720 | 39 | 4.5 |
| A | 9,400 | 21 | 2.25 |
| C | 10,120 | 21.5 | 2.12 |
| A | 10,240 | 19.0 | 1.85 |

* Base Rate—Rate of oxygen utilization by activated sludge alone after twenty-four hours aeration without feeding.

of their increasing suspended solids concentrations, it can readily be seen that the base rates do not increase accordingly. A comparison made on the basis of one gram of sludge also shows no constant value, since the results vary between 1.85 and 9.8 milligrams per hour per gram of dry sludge. It would seem that a better basis of comparison is the volatile solids content, since the biological life responsible for the oxygen utilization is more closely related to that part of the suspended solids. Such a comparison is made in Table II. In this table the

TABLE II.—*Comparison of Base Rates of Oxygen Utilization of Activated Sludges at 20° C. on the Basis of Volatile Solids Concentration*

| Sludge | Volatile Solids Conc. in P.p.m. | Base Rate in P.p.m. of $O_2$ per Hour | Mg. of $O_2$ per Hr. per Gram of Volatile Solids |
|---|---|---|---|
| 2E | 3,180 | 30 | 9.4 |
| AA | 3,450 | 34 | 9.9 |
| E | 4,000 | 52 | 13.0 |
| 2A | 4,030 | 20 | 5.0 |
| D | 4,300 | 45.5 | 10.6 |
| A | 6,300 | 21 | 3.35 |
| 2C | 6,400 | 39 | 6.1 |
| A | 6,800 | 19 | 2.8 |

sludges are arranged in order of increasing volatile solids content, but the base rates are seen not to increase in a like manner. A comparison with respect to oxygen used per gram of volatile solids, also shows a variation of from 2.8 to 13.0 milligrams per hour which definitely indicates that the volatile solids of one sludge may be entirely different in activity from the volatile solids of another sludge. With such wide variations in oxygen utilization per unit weight of suspended or volatile solids it does not appear possible to predict sludge activity from these characteristics alone.

## Discussion

The marked difference in the oxygen utilization rate curves produced by different activated sludges when oxidizing the same sewage and the similarity of the curves produced by a given sludge when oxidizing different sewages seems to indicate that we must seek for an explanation of the variations in the biological make-up of the sludges. Since no measure of the extent of nitrification was made during the course of any of these experiments, the authors are not in a position to state definitely whether the marked difference in amount of oxygen used by Sludges A and C to treat Sewage A (Graph 1) can be attributed to such a factor.

Because Sludge A, the one kept in the laboratory and fed on Sewage A for 60 days prior to its use in these experiments, showed a decidedly different type oxidation curve from those given by the other sludges used, this sludge was compared a second time to a fresh portion of Sludge A called 2A for differentiation. Results of this comparison again showed that the sludge being fed in the laboratory gave the same type of oxidation curve as the sludge obtained directly from the plant, the only difference of consequence being a higher activity for the new portions.

Of the oxygen utilization curves given by the different sludges, that for Sludge A is exceptional while those for Sludge C and Sludge D resemble each other very closely. The curves given by Sludge C on the two different occasions, 2/15/38 (Graph 1) and 3/21/38 (Graph 3), appear to be of exactly the same character. The curves produced by Sludge E (Graph 5) resemble those for Sludges C and D quite closely, except that the one given by Sludge E when oxidizing Sewage E shows a constant value for a short period at the beginning of the run. From these results, it appears that we may expect to encounter rate curves of at least three types in activated sludge-sewage oxidations.

The magnitude of the oxygen utilization by a given activated sludge when oxidizing sewage does not appear from these studies to be a fixed value depending only on sludge condition and activity as was suggested by Kessler and Nichols (8). In all the cases shown which involve oxidation of two different sewages by identical portions of the same sludge, the sewage having the greatest 5-day B.O.D. caused the greatest demand for oxygen per unit time. This is shown most markedly by Sludges A and E (Graph 5) when oxidizing Sewage A (5-day B.O.D.

= 302) and Sewage E (5-day B.O.D. = 563). In both cases the rate curves for oxidation of Sewage E were considerably above those for Sewage A.

Experience with the rate of oxygen usage by the various activated sludges in different stages of oxidation, when dosed with sewage, in conjunction with decreasing base rates of sludges alone has led the authors to believe that the activity of a sludge is greatly decreased as the percentage of ash content slowly increases. Grant, Hurwitz and Mohlman (7) have shown that the rate at which activated sludges use oxygen increases as the per cent of volatile solids in the sludge increases. A correlation of our data on the basis of both the volatile and suspended solids is shown in Figs. 1 and 2, and from them it can

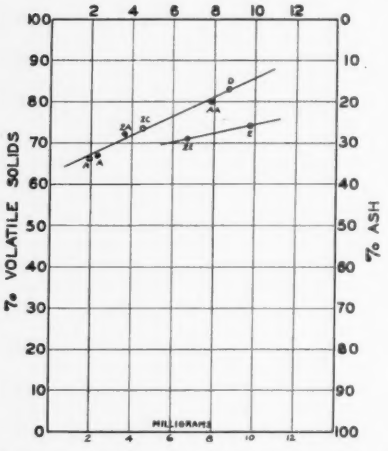



FIG. 1.—Oxygen used per gram of suspended solids per hour at 20° C.

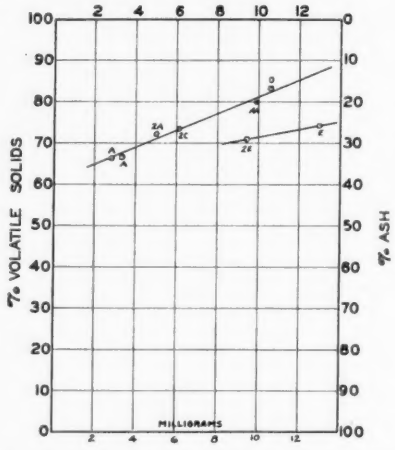



FIG. 2.—Oxygen used per gram of volatile solids per hour at 20° C.

be seen that the rate of oxygen usage per gram of volatile or of suspended solids, increases as the *percentage* of volatile solids increases in the sludge. This confirms the findings of Grant, Hurwitz and Mohlman and shows furthermore that the activity of the volatile solids is a function of the volatile solids to ash ratio. It is to be noted that the results obtained with Sludge E do not conform with those obtained with the other three sludges. No explanation is offered for this anomaly at this time. Extrapolation of the curves in Figs. 1 and 2 to intercept the "*y*" axes indicates that sludges with less than 60 per cent volatile solids would use very little oxygen if any at all. Further exploration of sludges having volatile solids contents of from 50 to 70 per cent is required to determine if the indicated straight line relationship holds over these ranges.

The activity of the various sludges as measured by their base rates of oxygen usage varied between 1.85 and 9.8 mg. of oxygen per hour per gram of dry sludge. We feel that the poorer sludges were those showing rates greater than 7.0 mg. per gram per hour. These findings

correlate with those reported by Ruchhoft, McNamee and Butterfield (3), who consider sludges using 2 to 6 mg. of oxygen per gram of sludge per hour as good sludges.

## Summary

1. Different activated sludges oxidizing identical portions of the same sewage may produce widely different types of oxygen utilization rate curves.

2. Identical portions of an activated sludge oxidizing different domestic sewages can be expected to produce approximately the same type curves.

3. The magnitude of the oxygen usage per unit of time by an activated sludge-sewage mixture is influenced by the strength of the sewage as measured by B.O.D.

4. Oxygen utilization by activated sludges alone (base rates) were found to vary from 1.85 to 9.8 milligrams per hour per gram of dry sludge.

5. No relationship was found between the base rates of oxygen usage by different activated sludges when compared on the basis of content of suspended solids, or volatile solids. Good correlation was obtained when base rates were compared with *percentage* of ash or volatile solids.

6. The character of the oxygen utilization rate curves obtained in this investigation indicates the possibility of at least three types of curves being produced by various activated sludge-sewage mixtures.

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# Plant Operation

## TRICKLING FILTER LOADINGS AT FORT WORTH, TEXAS

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Fort Worth, Texas, offers an excellent opportunity for observing trickling filter loadings, in that the sewage received at the city's treatment plant consists of a very strong domestic sewage to which has been added about 25 per cent (2.5 m.g.d.) of partly treated packinghouse wastes.

The method of treatment at the city plant consists of primary settling, pre-aeration without sludge return, secondary settling, trickling filters and final settling. Sludge is digested in separate tanks equipped for gas collection.

The filters are four in number, rectangular in shape, 384 ft. by 120 ft., having a total net area of 4.23 acres. The underdrain system consists of 4-in. vitrified split tile, laid on 8-in. centers with open joints. The stone consists of 8 ft. of hard limestone passing a 2.5-in. circular opening and retained on a 1.25 in. circular opening. The distribution system consists of 1-in. circular full spray, Type C, lock spindle, P.F.T. nozzles, spaced on 12 ft. centers at the vertices of equilateral triangles. The nozzle bases are screwed directly into cast-iron pipes laid horizontally on the top of the rock so that the top of the pipe is flush with the rock surface, thus eliminating the conventional galvanized pipe risers. Each filter is provided with a twin dosing tank with automatic siphons. The discharge time of one compartment is about 3.75 minutes.

For a long time we have observed a gradual falling-off in quality of the filter effluent throughout the week, and then a "recuperating effect" at the beginning of the next week.

This phenomenon is due to the variation in the strength of the raw sewage. A study of four years' analyses is shown in Table I.

It should be pointed out that there is no packinghouse waste admitted to our sewers on Sunday, and on Monday the packing plants work only approximately one-half day.

During the remainder of the week the packinghouse operation is fairly constant. The agreement of population equivalents on Tuesday, Wednesday, Thursday and Friday is quite remarkable. (No analyses are shown for Saturday sewages, since this would necessitate working our laboratory force on Sunday. Saturday's sewage will be approximately the same as the four preceding days.)

Naturally such a variation in the raw sewage is reflected in the

TABLE I.—*Average Analysis of Raw Sewage, Fort Worth, Texas*
From Jan. 1, 1935 to Dec. 31, 1938

| Day of Week | Sewage Flow Million Gallons | Suspended Solids P.p.m. | Settleable Solids C.c./L. | Nitrogen as $NH_3$ P.p.m. | Five Day B.O.D. P.p.m. | $H_2S$ P.p.m. | Chloride P.p.m. | pH | Population Equivalent |
|---|---|---|---|---|---|---|---|---|---|
| Sunday | 9.133 | 289 | 6.5 | 30.9 | 283 | — | 245 | — | 126,700 |
| Monday | 10.171 | 363 | 8.0 | 31.1 | 377 | 4.1 | 317 | 7.6 | 188,000 |
| Tuesday | 10.994 | 371 | 7.0 | 32.8 | 460 | 4.1 | 425 | 7.5 | 247,900 |
| Wednesday | 10.975 | 375 | 7.0 | 33.6 | 463 | 3.9 | 436 | 7.5 | 249,100 |
| Thursday | 11.068 | 371 | 6.8 | 33.8 | 456 | 4.9 | 435 | 7.5 | 247,400 |
| Friday | 10.991 | 370 | 6.7 | 34.3 | 458 | 4.2 | 449 | 7.5 | 246,800 |
| Saturday | 11.056 | — | — | — | — | — | — | — | — |

Population equivalent based on .17 lb. B.O.D.

TABLE II.—*Average Analysis of Filter Influent, Fort Worth, Texas*
From Jan. 1, 1935 to Dec. 31, 1938

| Day of Week | Susp. Solids P.p.m. | Nitrogen as $NH_3$ P.p.m. | Five Day B.O.D. P.p.m. | $H_2S$ P.p.m. | pH | Population Equivalent |
|---|---|---|---|---|---|---|
| Sunday | 98 | 32.3 | 167 | — | — | 74,800 |
| Monday | 110 | 33.6 | 203 | 2.6 | 7.7 | 101,200 |
| Tuesday | 136 | 34.9 | 284 | 3.3 | 7.6 | 153,100 |
| Wednesday | 143 | 36.0 | 299 | 3.6 | 7.6 | 160,900 |
| Thursday | 143 | 36.7 | 301 | 4.5 | 7.7 | 163,300 |
| Friday | 141 | 37.0 | 300 | 4.3 | 7.6 | 161,600 |
| Saturday | — | — | — | — | — | — |

TABLE III.—*Average Analysis of Filter Effluent, Fort Worth, Texas*
From Jan. 1, 1935 to Dec. 31, 1938

| Day of Week | Susp. Solids P.p.m. | Nitrogen as $NH_3$ P.p.m. | Five Day B.O.D. P.p.m. | N as $NO_2$ plus $NO_3$ P.p.m. | Dis. Oxygen P.p.m. | $H_2S$ P.p.m. | pH | Population Equivalent |
|---|---|---|---|---|---|---|---|---|
| Sunday | 89 | 11.8 | 32 | 9.4 | 1.9 | — | — | 14,330 |
| Monday | 88 | 13.0 | 35 | 10.4 | 1.8 | 0.1 | 7.4 | 17,450 |
| Tuesday | 85 | 14.3 | 43 | 7.7 | 1.3 | 0.2 | 7.4 | 23,170 |
| Wednesday | 89 | 15.5 | 47 | 5.6 | 1.1 | 0.1 | 7.3 | 25,290 |
| Thursday | 91 | 16.2 | 48 | 5.5 | 1.1 | 0.2 | 7.5 | 26,040 |
| Friday | 90 | 16.8 | 47 | 5.5 | 1.1 | 0.2 | — | 25,320 |
| Saturday | — | — | — | — | — | — | — | — |

trickling filter performance. Table II shows the composition of the sewage applied to the filters, and Table III shows the composition of the filter effluent. Figure 1 shows the relationship between the filter loading and the oxidized nitrogen for a four-year period beginning January 1, 1935.

During this four-year interval there were four different methods or periods of plant operation, as follows:

Period A.

582 days from Jan. 1, 1935 to Oct. 13, 1936. During this time Imhoff tank effluent was placed directly on the filters.

Period B.

92 days from Oct. 14, 1936 to Dec. 31, 1936, and from Jan. 13, 1937 to Jan. 31, 1937. Primary tank effluent was placed directly on the filters. (The Imhoff tanks having been converted into primary tanks.)

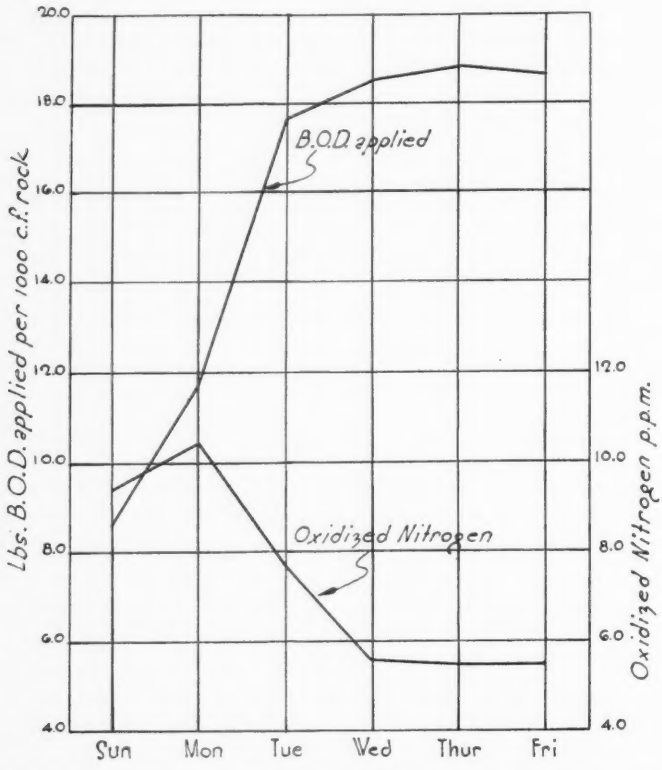


FIG 1.—Relationship between B.O.D. applied to trickling filter and oxidized nitrogen in effluent. Fort Worth, Texas. From Jan. 1, 1935 to Dec. 31, 1938.

Period C.

161 days from Jan. 1, 1937 to Jan. 12, 1937 and from Feb. 1, 1937 to June 30, 1937. Primary tank effluent was aerated and placed directly on the trickling filters. Amount of air, 0.43 cu. ft. per gallon. Aeration period 5.5 hours. No sludge return.

Period D.

535 days from July 1, 1937 to Dec. 31, 1938. Primary tank ef-

fluent was aerated, passed through secondary settling tanks, thence to trickling filters. Amount of air 0.45 cu. ft. per gallon, period 5.2 hours. Settling time 1.6 hours. No sludge return.

Tables IV to VII show the composition of the filter influent and effluent and the filter loadings for these periods.

TABLE IV.—*Period A*

Imhoff effluent direct to filters—582 days from Jan. 1, 1935 to Oct. 13, 1936

Filter Influent

| Day | Susp. Solids P.p.m. | B.O.D. P.p.m. | $NH_3$ P.p.m. | $H_2S$ P.p.m. | pH | Dis. Oxygen P.p.m. | N as $NO_2+NO_3$ P.p.m. |
|---|---|---|---|---|---|---|---|
| Sun. | 101 | 177 | 34.4 | | | | |
| Mon. | 119 | 227 | 36.1 | 5.1 | 7.6 | | |
| Tue. | 141 | 292 | 37.7 | 6.1 | 7.5 | | |
| Wed. | 143 | 298 | 37.9 | 6.6 | 7.4 | | |
| Thur. | 144 | 293 | 38.0 | 6.8 | 7.7 | | |
| Fri. | 143 | 292 | 38.0 | 6.6 | | | |
| Sat. | | | | | | | |
| Ave. | 132 | 263 | 37.0 | 6.2 | 7.6 | | |

Filter Effluent

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sun. | 91 | 38 | 12.4 | | | 1.6 | 9.8 |
| Mon. | 97 | 48 | 13.9 | 0.1 | 7.5 | 1.4 | 9.8 |
| Tue. | 94 | 56 | 15.5 | 0.1 | 7.6 | 1.0 | 6.9 |
| Wed. | 97 | 59 | 16.3 | 0.1 | 7.3 | 1.0 | 5.1 |
| Thur. | 101 | 59 | 16.8 | 0.1 | 7.9 | 1.0 | 4.9 |
| Fri. | 98 | 57 | 16.8 | 0.1 | | 1.0 | 5.4 |
| Sat. | | | | | | | |
| Ave. | 96 | 53 | 15.3 | 0.1 | 7.6 | 1.2 | 7.0 |

Filter Loading

| Day | Flow Mill. Gals. | Influent | | Effluent | | Lb. B.O.D. Applied | | | Lb. B.O.D. Removed | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B.O.D. P.p.m. | B.O.D. Lb. | B.O.D. P.p.m. | B.O.D. Lb. | Per Acre | Per Acre Foot | Per 1000 Cu. Ft. | Total | Per Acre | Per Acre Foot | Per 1000 Cu. Ft. |
| Sun. | 8.405 | 177 | 12,397 | 38 | 2,662 | 2,931 | 366 | 8.40 | 9,735 | 2,301 | 288 | 6.61 |
| Mon. | 9.540 | 227 | 18,047 | 48 | 3,816 | 4,266 | 533 | 12.23 | 14,231 | 3,364 | 421 | 9.66 |
| Tue. | 9.904 | 292 | 24,100 | 56 | 4,622 | 5,697 | 712 | 16.34 | 19,478 | 4,605 | 576 | 13.22 |
| Wed. | 10.154 | 298 | 25,216 | 59 | 4,992 | 5,961 | 745 | 17.10 | 20,224 | 4,781 | 598 | 13.73 |
| Thur. | 10.290 | 293 | 25,125 | 59 | 5,059 | 5,940 | 743 | 17.06 | 20,066 | 4,744 | 593 | 13.61 |
| Fri. | 10.129 | 292 | 24,647 | 57 | 4,811 | 5,827 | 728 | 16.71 | 19,836 | 4,689 | 586 | 13.45 |
| Sat. | 10.224 | | | | | | | | | | | |
| Ave. | 9.807 | 263 | 21,589 | 53 | 4,327 | 5,104 | 638 | 14.64 | 17,262 | 4,081 | 510 | 11.71 |

TABLE V.—*Period B*

**Primary tank effluent direct to filters. 92 Days from Oct. 14, 1936 to Dec. 31, 1936, and from Jan. 13, 1937 to Jan. 31, 1937**

Filter Influent

| Day | Susp. Solids P.p.m. | B.O.D. P.p.m. | $NH_3$ P.p.m. | $H_2S$ P.p.m. | pH | Dis. Oxygen P.p.m. | N as $NO_2+NO_3$ P.p.m. |
|---|---|---|---|---|---|---|---|
| Sun. | 111 | 143 | 28.5 | | | | |
| Mon. | 132 | 258 | 31.3 | 1.9 | | | |
| Tue. | 159 | 328 | 32.4 | 1.7 | 7.6 | | |
| Wed. | 153 | 303 | 30.7 | 2.3 | | | |
| Thur. | 145 | 289 | 31.6 | 2.8 | | | |
| Fri. | 145 | 299 | 31.3 | 3.9 | | | |
| Sat. | | | | | | | |
| Ave. | 141 | 270 | 31.0 | 2.5 | 7.6 | | |

Filter Effluent

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sun. | 107 | 39 | 11.6 | | | 2.5 | 10.5 |
| Mon. | 90 | 44 | 13.6 | 0.1 | | 1.8 | 10.6 |
| Tue. | 94 | 56 | 15.3 | 0.1 | 7.5 | 1.2 | 7.7 |
| Wed. | 98 | 58 | 15.6 | 0.2 | | 1.0 | 5.1 |
| Thur. | 97 | 57 | 15.3 | 0.1 | | 1.3 | 6.5 |
| Fri. | 92 | 56 | 15.6 | 0.1 | | 1.5 | 6.0 |
| Sat. | | | | | | | |
| Ave. | 96 | 52 | 14.5 | 0.1 | 7.5 | 1.6 | 7.7 |

Filter Loading

| Day | Flow Mill. Gals. | Influent | | Effluent | | Lb. B.O.D. Applied | | | Lb. B.O.D. Removed | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B.O.D. P.p.m. | B.O.D. Lb. | B.O.D. P.p.m. | B.O.D. Lb. | Per Acre | Per Acre Foot | Per 1000 Cu. Ft. | Total | Per Acre | Per Acre Foot | Per 1000 Cu. Ft. |
| Sun. | 10.738 | 143 | 12,796 | 39 | 3,490 | 3,025 | 378 | 8.68 | 9,306 | 2,200 | 275 | 6.31 |
| Mon. | 11.803 | 258 | 25,376 | 44 | 4,328 | 5,999 | 750 | 17.22 | 21,048 | 4,976 | 622 | 14.28 |
| Tue. | 12.655 | 328 | 34,590 | 56 | 5,906 | 8,177 | 1,022 | 23.46 | 28,684 | 6,781 | 848 | 19.47 |
| Wed. | 11.549 | 303 | 29,161 | 58 | 5,582 | 6,894 | 862 | 19.79 | 23,579 | 5,574 | 697 | 16.00 |
| Thur. | 12.354 | 289 | 29,753 | 57 | 5,868 | 7,034 | 879 | 20.18 | 23,885 | 5,647 | 706 | 16.21 |
| Fri. | 11.951 | 299 | 29,778 | 56 | 5,577 | 7,040 | 880 | 20.20 | 24,201 | 5,721 | 715 | 16.41 |
| Sat. | 12.850 | | | | | | | | | | | |
| Ave. | 11.986 | 270 | 26,909 | 52 | 5,125 | 6,362 | 795 | 18.26 | 21,784 | 5,150 | 644 | 14.78 |

TABLE VI.—*Period C*

Primary tank effluent aerated, then directly to filters. 161 days. From Jan. 1, 1937 to Jan. 12, 1937, and from Feb. 1, 1937 to June 30, 1937

Air, 0.43 c.f./g. Aeration time, 5.5 hr. No sludge return

Filter Influent

| Day | Susp. Solids P.p.m. | B.O.D. P.p.m. | $NH_3$ P.p.m. | $H_2S$ P.p.m. | pH | Dis. Oxygen P.p.m. | N as $NO_2 + NO_3$ P.p.m. |
|---|---|---|---|---|---|---|---|
| Sun. | 126 | 167 | 30.1 | | | | |
| Mon. | 146 | 227 | 31.6 | 0.4 | | | |
| Tue. | 169 | 305 | 32.7 | 0.5 | 7.6 | | |
| Wed. | 182 | 335 | 33.4 | 0.6 | | | |
| Thur. | 177 | 335 | 34.5 | 0.4 | | | |
| Fri. | 174 | 358 | 34.4 | 0.4 | | | |
| Sat. | | | | | | | |
| Ave. | 162 | 288 | 32.8 | 0.5 | 7.6 | | |

Filter Effluent

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sun. | 116 | 39 | 13.5 | | | 2.5 | 9.2 |
| Mon. | 105 | 39 | 15.2 | 0.2 | | 2.2 | 10.0 |
| Tue. | 105 | 47 | 15.9 | 0.3 | 7.3 | 1.6 | 7.4 |
| Wed. | 109 | 48 | 16.6 | 0.2 | | 1.3 | 5.8 |
| Thur. | 111 | 52 | 17.6 | 0.2 | | 1.3 | 5.3 |
| Fri. | 110 | 50 | 12.9 | 0.3 | | 1.2 | 5.7 |
| Sat. | | | | | | | |
| Ave. | 109 | 46 | 15.3 | 0.2 | 7.3 | 1.7 | 7.2 |

Filter Loading

| Day | Flow Mil. Gals. | Influent | | Effluent | | Lb. B.O.D. Applied | | | Lb. B.O.D. Removed | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B.O.D. P.p.m. | B.O.D. Lb. | B.O.D. P.p.m. | B.O.D. Lb. | Per Acre | Per Acre Foot | Per 1000 Cu. Ft. | Total | Per Acre | Per Acre Foot | Per 1000 Cu. Ft. |
| Sun. | 10.259 | 167 | 14,277 | 39 | 3,334 | 3,375 | 422 | 9.69 | 10,943 | 2,587 | 323 | 7.42 |
| Mon. | 11.360 | 227 | 21,489 | 39 | 3,692 | 5,080 | 635 | 14.58 | 17,797 | 4,207 | 526 | 12.08 |
| Tue. | 12.357 | 305 | 31,407 | 47 | 4,840 | 7,425 | 928 | 21.30 | 26,567 | 6,281 | 785 | 18.02 |
| Wed. | 12.237 | 335 | 34,162 | 48 | 4,895 | 8,076 | 1,010 | 23.19 | 29,267 | 6,919 | 865 | 19.86 |
| Thur. | 12.237 | 335 | 34,162 | 52 | 5,303 | 8,076 | 1,010 | 23.19 | 28,859 | 6,822 | 853 | 19.58 |
| Fri. | 11.901 | 358 | 35,505 | 50 | 4,959 | 8,394 | 1,049 | 24.08 | 30,546 | 7,221 | 903 | 20.73 |
| Sat. | 12.247 | | | | | | | | | | | |
| Ave. | 11.800 | 288 | 28,500 | 46 | 4,504 | 6,738 | 842 | 19.34 | 23,997 | 5,673 | 709 | 16.28 |

TABLE VII.—*Period D*

**Primary tank effluent aerated, then to secondary settling, then to filters. 535 days. From July 1, 1937 to Dec. 31, 1938**

**Air, 0.45 c.f./g. Aeration time, 5.2 hr. Settling time, 1.6 hr. No sludge return**

Filter Influent

| Day | Susp. Solids P.p.m. | B.O.D. P.p.m. | $NH_3$ P.p.m. | $H_2S$ P.p.m. | pH | Dis. Oxygen P.p.m. | N as $NO_2 + NO_3$ P.p.m. |
|---|---|---|---|---|---|---|---|
| Sun. | 82 | 157 | 31.3 | | | | |
| Mon. | 85 | 156 | 31.6 | 0.8 | 7.8 | | |
| Tue. | 115 | 257 | 32.8 | 1.4 | 7.7 | | |
| Wed. | 130 | 287 | 35.4 | 2.6 | 7.7 | | |
| Thur. | 132 | 298 | 36.2 | 3.2 | 7.8 | | |
| Fri. | 126 | 297 | 37.6 | 2.7 | 7.6 | | |
| Sat. | | | | | | | |
| Ave. | 112 | 242 | 34.2 | 2.1 | 7.7 | | |

Filter Effluent

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sun. | 76 | 20 | 10.6 | | | 2.0 | 8.7 |
| Mon. | 71 | 17 | 11.1 | 0.2 | 7.4 | 2.1 | 11.1 |
| Tue. | 66 | 23 | 12.0 | 0.2 | 7.3 | 1.5 | 8.7 |
| Wed. | 70 | 28 | 14.3 | 0.1 | 7.3 | 1.2 | 6.4 |
| Thur. | 71 | 29 | 15.1 | 0.2 | 7.5 | 1.2 | 6.0 |
| Fri. | 71 | 30 | 16.6 | 0.2 | 7.8 | 1.1 | 5.5 |
| Sat. | | | | | | | |
| Ave. | 71 | 25 | 13.3 | 0.2 | 7.5 | 1.5 | 7.7 |

Filter Loading

| Day | Flow Mill. Gals. | Influent | | Effluent | | Lb. B.O.D. Applied | | | Lb. B.O.D. Removed | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B.O.D. P.p.m. | B.O.D. Lb. | B.O.D. P.p.m. | B.O.D. Lb. | Per Acre | Per Acre Foot | Per 1000 Cu. Ft. | Total | Per Acre | Per Acre Foot | Per 1000 Cu. Ft. |
| Sun. | 9.377 | 157 | 12,268 | 20 | 1,563 | 2,900 | 363 | 8.33 | 10,705 | 2,531 | 316 | 7.25 |
| Mon. | 10.307 | 156 | 13,399 | 17 | 1,460 | 3,168 | 396 | 9.09 | 11,939 | 2,822 | 353 | 8.10 |
| Tue. | 11.605 | 257 | 24,854 | 23 | 2,224 | 5,876 | 735 | 16.87 | 22,630 | 5,350 | 669 | 15.36 |
| Wed. | 11.496 | 287 | 27,495 | 28 | 2,682 | 6,500 | 813 | 18.66 | 24,813 | 5,866 | 733 | 16.83 |
| Thur. | 11.453 | 298 | 28,442 | 29 | 2,768 | 6,724 | 841 | 19.31 | 25,674 | 6,070 | 759 | 17.42 |
| Fri. | 11.641 | 297 | 28,811 | 30 | 2,910 | 6,811 | 851 | 19.54 | 25,901 | 6,123 | 765 | 17.56 |
| Sat. | 11.399 | | | | | | | | | | | |
| Ave. | 11.040 | 242 | 22,545 | 25 | 2,268 | 5,330 | 667 | 15.30 | 20,277 | 4,794 | 599 | 13.75 |

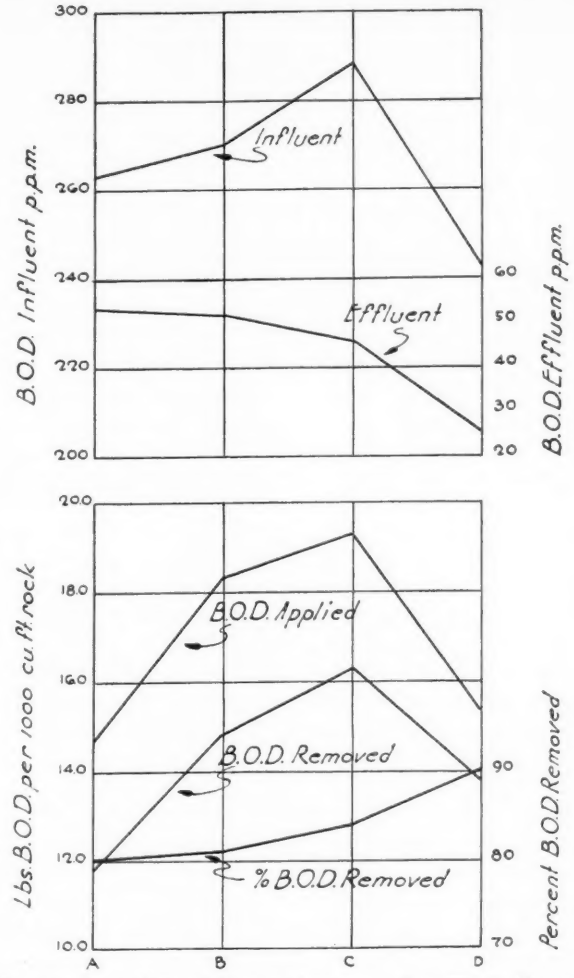


FIG. 2.—Comparison of filter performance. Fort Worth, Texas.

Figure 2 shows a comparison of filter loadings and performance for these four periods.

## REMARKS

During periods A and B, there was some slight ponding, while during periods C and D there was none whatever.

We have tried to correlate the filter loadings with odors but were unable to find any direct relation. It might be said in passing that our filters are usually giving off odors. Odor factors for the four periods were 77, 70, 67 and 77 respectively. (For odor factor determination see THIS JOURNAL, Jan., 1939.)

No attempt is made here to compare the performance of filters at Fort Worth with other plants, but only to point out the high loadings that may be applied in localities having a similar climatic condition.

# SOLIDS BALANCING

By G. E. Flower, Chester B. Budd and Charles Hauck

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## Description and Operation

The Southerly Sewage Treatment Plant at Cleveland, Ohio (for the period of this report), included bar grates, grit chambers, Imhoff tanks, trickling filters and humus tanks. The sludge collected in the humus tanks was pumped into the digestion compartments of the Imhoff tanks for digestion. The plant treated stormwater and industrial wastes mixed with sanitary sewage. The industrial wastes are mostly iron wastes from surrounding steel mills. At times these iron wastes run as high as 300 to 400 p.p.m. iron, but when the steel mills are only in partial operation, the iron content of the sewage averages about 10 p.p.m.

## Discussion

If suspended solids are determined in the influent and effluent of a settling tank, and the flow is known, the solids deposition in the tank can be calculated. Similarly, when the settled solids are pumped to a digestion tank, the solids can again be calculated from the flow of raw sludge and the suspended solids content. Theoretically the weight of solids by the two methods should be the same. A review of some of the literature on this subject shows that marked discrepancies sometimes occur. These discrepancies were discussed at a meeting of the Central States Sewage Works Association at Menasha, Wisconsin. The conclusions of these discussions were (1) "From all that was heard in this discussion, and also previous discussions, it seemed apparent that solids removals calculated from sewage and effluent analyses may be so far from actual accomplishments that no dependability can be placed on such accounting, either as to revealing efficiencies of settling processes or in solids accounting. The use of large sludge samples for solids determinations, careful measurement of sludge volumes and truly representative sampling, should become approved standard practice.—Ed." On this same question Greeley (2) points out the following: "It is difficult at many sludge digestion plants to determine with reasonable accuracy the total amount of suspended solids being handled in the digestion tank. Quantities are computed either from the volume of the sludge pumped and its solids content, or from the amount of sewage and the suspended matter removed. The results of these computations may vary widely. The reason for this variation is not apparent. Possibly it is due to the rapid pumping of raw sludge, which does not permit accurate sampling, or to inaccurate determinations of the moisture content of the sludge. Of the two methods, the one based on sewage flow and suspended solids removed appears to be

the more reliable. In general, difficulties in sampling constitute an important factor."

These then are some of the difficulties encountered in solids accounting when figured from sewage as against raw sludge. When the raw sludge is allowed to undergo digestion and solids balances are attempted, taking into account the losses due to digestion, the difficulties encountered are magnified. In accounting for solids losses a fixed percentage of total solids deposited is sometimes assumed as destroyed. This figure varies with the wastes treated, *i.e.* whether they are sanitary wastes, storm water, industrial wastes or combinations of these three. Some evidence (3) has been presented to show that there is a linear relationship between the percentage of volatile matter in raw sludge and the percentage reduction of original volatile matter when sludge is ripe. As the percentage of volatile solids in the raw sludge increases, so does the per cent destroyed. The equation of the line is approximately of the form $y = 0.53x + 36$ where $y$ is the percentage of volatile matter in raw sludge and $x$ is the percentage reduction of original volatile matter when sludge is ripe. This relationship, in the reference cited, appears to be a good grouping of the plotted points about the line whose equation is as above. However, the data (Table VI) from the article by Greeley, (2) when plotted in the same manner, show little relationship as is evidenced by looking at the accompanying graph.

The claim is sometimes made that a daily composite sewage sample will suffer pectization or peptization. In this way the suspended solids determination would introduce an error in the ideal balance between the method of sewage analysis and that of sludge analysis. If this is true then a computation of the sewage solids on the basis of total solids should yield more reliable results. There should also be a closer correlation; not only on this account alone but because of the fact that solids in sludges are, as a rule, run on a total solids and not on a suspended solids basis. If there is any point in this statement, then solids depositions figured on the basis of total solids should be different from those figured on the basis of suspended solids in all those instances where pectization, peptization or conversion of solids into true solution takes place.

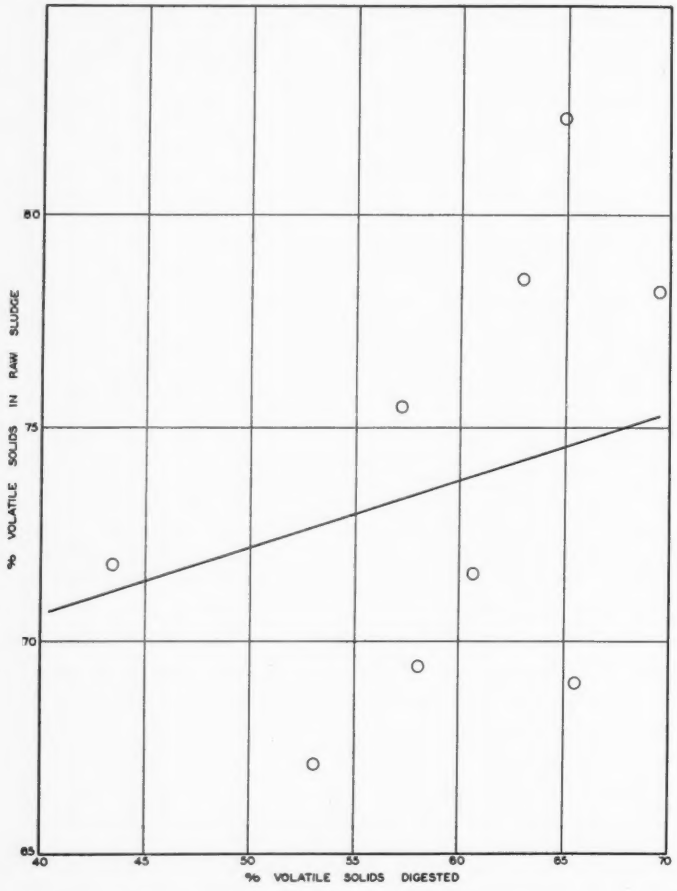
## Explanation of Data

Aside from the obstacles inherent in the assumption of a fixed percentage destruction, there is a question as to whether the balance should be attempted on the basis of the removal of suspended solids or the removal of total solids. It appears reasonable to suppose that the difference between these two methods should be small.

The solids balance, as presented here, is not based upon a fixed percentage destruction of solids deposited. Account has been made of all measurable quantities at the beginning and end of each year and the difference assumed to be loss by digestion. In other words, a determination has been made of all solids deposited in the Imhoff tanks

and of all solids withdrawn from the tanks as digested sludge, and the difference is assumed as the destruction of organic matter by digestion.

Several treatments of the data have been made but, in all cases, the balance has been attempted on the basis of suspended solids removal as well as total solids removal. By suspended solids and total solids removal is meant the deposition of solids in the Imhoff tanks and




humus tanks calculated on the basis of sewage flow and laboratory analyses of 24 hour composite samples collected before and after treatment by these two types of tanks.

In the first treatment of the data presented, the year by year apparent destruction of solids is determined. For the year 1928, when the plant first went into service, no data are available as to the total solids of the raw sewage. No sludge was withdrawn in 1928 and but little in 1929. As a result, the digestion loss appears quite high; most

of the solids remained in the tanks and were disregarded in this treatment. In 1930 the solids drawn as sludge were twice as much as in the previous year and consequently the digestion loss appears low. This again is due to the fact that no account has been made of the solids still in the tanks. In 1931 the removal of digested sludge was so high that a negative digestion loss was indicated. For the years 1932, 1933 and 1934 the digestion loss appears to have been fairly constant. For 1935 and 1936 the loss was constant on the basis of total solids removal, but erratic on the basis of suspended solids removal. The discrepancy between the two methods of computation varies from 6.2 per cent for 1935 to 22.4 per cent for 1937. The agreement does not appear to be close.

The second treatment of the data is the same as the first with the additional precaution of taking into account the solids retained in the Imhoff tanks on the basis of sludge soundings. The first sludge soundings were made in 1934 so that this treatment covers only four years of plant operation. With the exception of 1934 the data, on the basis of total solids, are quite consistent whereas the data on the basis of suspended solids are quite erratic. A reduction of total solids of about 20 per cent, as brought out in the data for 1935–1937 (total solids basis), seems to be a reasonable figure although a bit low.

The third treatment of the data gives a solids accounting figured cumulatively for the years 1933–1937 inclusive. The data, on the basis of suspended solids and total solids, is quite consistent. The average per cent destruction of dry solids for these years is 11.9 per cent on the basis of suspended solids and 23.2 per cent on the basis of total solids. The data, although consistent in themselves, regardless of which way they were figured, whether on total or suspended solids basis, show striking differences in comparing the results of one method with those of the other. The percentage reduction of dry solids as figured from total solids (23.2 per cent) is practically twice that when figured from suspended solids (11.9 per cent). This discrepancy is quite high. The difference may be explained on the basis that the dry solids deposited, as figured on total solids, are higher than those figured as suspended solids. The other solids data (solids withdrawn and solids still in tanks) are the same as computed both by total solids and suspended solids. Because of this the solids destroyed are higher on a total solids basis. This in turn makes the percentage destruction of solids, as figured on total solids, consistently higher than when figured on suspended solids.

## Summary

The following points briefly summarize the question of solids balancing:

1. It is difficult to determine with reasonable accuracy the total amount of solids being handled. Quantities are computed either from the volume of the sludge pumped and its solids content or from the amount of sewage and the suspended matter removed. The results

of these computations may vary widely. The reason for this variation is not apparent. Possibly it is due to inaccurate sampling and inaccurate determinations of the moisture content of the sludge.

2. Schlenz has presented some data to show that there is a linear relationship between the percentage of volatile matter in raw sludge and the percentage reduction of original volatile matter when sludge is ripe. This relationship tends to show that as the volatile solids in the raw sludge increase so also does the per cent that is destroyed. The data, as compiled by Greeley and shown in Fig. 1, fail to show this relationship.

3. It appears to make a difference whether solids balances are attempted on the basis of total solids removal or on the basis of suspended solids removal. In spite of the fact that seemingly everywhere sedimentation tank performance is based on suspended solids removal it appears, from this treatment, that performance should be based on total solids removal. In view of the fact that sludge analyses are usually determined on a total solids basis it seems more reasonable to calculate the solids in the sewage on the basis of total solids. If suspended solids go into true solution, or pectization and peptization effects take place, they do not affect the total solids determination whereas they do affect the suspended solids determination. Even if these effects do not occur in the sewage samples the total solids determinations are more reliable than the suspended solids determinations in evaluating solids removals in sewage.

4. It is perhaps a more reliable procedure in solids balancing, where losses due to digestion take place, not to assume a fixed percentage loss of solids, but to determine the apparent percentage loss and, if this figure is fairly constant, to assume that a solids balance has been effected, if at the same time the determined digestion loss is reasonable.

5. Solids balances could perhaps be best accounted for by the constancy of fixed solids. The fixed solids going into the digesters as raw sludge should equal the fixed solids coming out of the digesters as digested sludge. This is based on the assumption that there is no conversion of fixed solids to volatile solids or of volatile solids to fixed

TABLE I.—*Southerly Sewage Treatment Plant*

Per Cent Volatile Matter in Daily Composite Samples—Monthly Averages for 1938

| Month | Total Solids | | Suspended Solids | |
|---|---|---|---|---|
| | Raw | Settled | Raw | Settled |
| March | 44 | 41 | 62 | 61 |
| April | 41 | 38 | 64 | 60 |
| May | 50 | 46 | 71 | 67 |
| June | 49 | 45 | 68 | 60 |
| July | 43 | 44 | 50 | 53 |
| August | 49 | 46 | 67 | 64 |
| Average | 46 | 43 | 67 | 61 |

TABLE II.—*Solids Balance at the Southerly Sewage Treatment Plant*

No Account Taken of Solids Remaining in Imhoff Tanks

| | On Basis of Suspended Solids Removal | On Basis of Total Solids Removal | On Basis of Suspended Solids Removal | On Basis of Total Solids Removal |
|---|---|---|---|---|
| | 1928 | | 1933 | |
| Calculated Fresh Solids (lb.) | 485,260 | | 11,688,000 | 13,768,000 |
| Calculated Humus Solids (lb.) | 65,238 | | 1,445,000 | 1,632,000 |
| Calculated Total Solids (lb.) | 550,498 | | 13,133,000 | 15,400,000 |
| Removal of Solids as Sludge (lb.) | | | 9,517,000 | 9,517,000 |
| Apparent Destruction of Solids (lb.) | | | 3,616,000 | 5,883,000 |
| Apparent Destruction of Solids (%) | | | 27.5 | 38.2 |
| | 1929 | | 1934 | |
| Calculated Fresh Solids (lb.) | 2,646,000 | 3,343,000 | 8,725,000 | 11,713,000 |
| Calculated Humus Solids (lb.) | 172,000 | 208,000 | 1,482,000 | 1,170,000 |
| Calculated Total Solids (lb.) | 2,818,000 | 3,551,000 | 10,207,000 | 12,883,000 |
| Removal of Solids as Sludge (lb.) | 998,000 | 998,000 | 7,174,000 | 7,174,000 |
| Apparent Destruction of Solids (lb.) | 1,820,000 | 2,553,000 | 3,033,000 | 5,709,000 |
| Apparent Destruction of Solids (%) | 64.6 | 71.9 | 29.7 | 44.3 |
| | 1930 | | 1935 | |
| Calculated Fresh Solids (lb.) | 2,450,000 | 2,827,000 | 8,639,000 | 9,741,000 |
| Calculated Humus Solids (lb.) | 183,000 | 183,000 | 1,406,000 | 1,055,000 |
| Calculated Total Solids (lb.) | 2,633,000 | 3,010,000 | 10,045,000 | 10,796,000 |
| Removal of Solids as Sludge (lb.) | 2,600,000 | 2,600,000 | 8,974,000 | 8,974,000 |
| Apparent Destruction of Solids (lb.) | 33,000 | 410,000 | 1,071,000 | 1,822,000 |
| Apparent Destruction of Solids (%) | 1.3 | 13.6 | 10.7 | 16.9 |
| | 1931 | | 1936 | |
| Calculated Fresh Solids (lb.) | 3,445,000 | 3,336,000 | 7,771,000 | 9,559,000 |
| Calculated Humus Solids (lb.) | 465,000 | 398,000 | 461,000 | 922,000 |
| Calculated Total Solids (lb.) | 3,910,000 | 3,734,000 | 8,232,000 | 10,481,000 |
| Removal of Solids as Sludge (lb.) | 5,416,000 | 5,416,000 | 8,878,000 | 8,878,000 |
| Apparent Destruction of Solids (lb.) | *1,506,000 | *1,682,000 | *646,000 | 1,603,000 |
| Apparent Destruction of Solids (%) | * 38.5 | * 45.0 | * 7.8 | 15.3 |
| | 1932 | | 1937 | |
| Calculated Fresh Solids (lb.) | 9,202,000 | 9,948,000 | 6,799,000 | 8,920,000 |
| Calculated Humus Solids (lb.) | 787,000 | 751,000 | | |
| Calculated Total Solids (lb.) | 9,989,000 | 10,699,000 | 6,799,000 | 8,920,000 |
| Removal of Solids as Sludge (lb.) | 7,002,000 | 7,002,000 | 6,396,000 | 6,396,000 |
| Apparent Destruction of Solids (lb.) | 2,987,000 | 3,697,000 | 403,000 | 2,524,000 |
| Apparent Destruction of Solids (%) | 29.9 | 34.6 | 5.9 | 28.3 |

* Indicates increase instead of destruction.

TABLE III.—*Sludge in Imhoff Tanks*

| Date | Sludge Elevation Ft. | Number of Soundings | Equivalent Volume Cu. Yds. | Equivalent Wt. Dry Solids Lb. |
|---|---|---|---|---|
| 1–9–34 | 11.3 | 14 | 29,280 | 5,284,000 |
| 1–9–35 | 8.8 | 24 | 23,520 | 4,244,000 |
| 1–2–36 | 7.4 | 17 | 20,160 | 3,638,000 |
| 1–5–37 | 6.1 | 18 | 17,280 | 3,118,000 |
| 1–3–38 | 8.5 | 14 | 22,800 | 4,114,000 |

The equivalent weight of dry solids was calculated on the basis of a specific gravity of 1.03 and a moisture content of 89.6 per cent. These figures are average for all years of plant operation.

TABLE IV.—*Yearly Solids Balance*

Solids in Imhoff Tanks Accounted for

| | On Basis of Suspended Solids Removal | On Basis of Total Solids Removal |
|---|---|---|
| | 1934 | |
| Dry Solids Deposited (lb.) | 10,207,000 | 12,883,000 |
| Dry Solids Withdrawn (lb.) | 7,174,000 | 7,174,000 |
| Balance (lb.) | 3,033,000 | 5,709,000 |
| Excess Drawn from Imhoff Tanks (lb.) | 1,040,000 | 1,040,000 |
| Dry Solids Destroyed (lb.) | 4,073,000 | 6,749,000 |
| Per Cent Destroyed | 39.9 | 52.4 |
| | 1935 | |
| Dry Solids Deposited (lb.) | 10,045,000 | 10,796,000 |
| Dry Solids Withdrawn (lb.) | 8,974,000 | 8,974,000 |
| Balance (lb.) | 1,071,000 | 1,822,000 |
| Excess Drawn from Imhoff Tanks (lb.) | 606,000 | 606,000 |
| Dry Solids Destroyed (lb.) | 1,677,000 | 2,428,000 |
| Per Cent Destroyed | 16.7 | 22.5 |
| | 1936 | |
| Dry Solids Deposited (lb.) | 8,232,000 | 10,481,000 |
| Dry Solids Withdrawn (lb.) | 8,878,000 | 8,878,000 |
| Balance (lb.) | * 646,000 | 1,603,000 |
| Excess Drawn from Imhoff Tanks (lb.) | 520,000 | 520,000 |
| Dry Solids Destroyed (lb.) | * 126,000 | 2,123,000 |
| Per Cent Destroyed | * 1.5 | 20.3 |
| * Designates Increase | | |
| | 1937 | |
| Dry Solids Deposited (lb.) | 6,799,000 | 8,920,000 |
| Dry Solids Withdrawn (lb.) | 6,396,000 | 6,396,000 |
| Balance (lb.) | 403,000 | 2,524,000 |
| Excess Drawn from Imhoff Tanks (lb.) | 996,000 | 996,000 |
| Dry Solids Destroyed (lb.) | * 593,000 | 1,528,000 |
| Per Cent Destroyed | * 8.7 | 17.1 |
| * Designates Increase | | |

* Excess drawn from Imhoff tanks represents the solids necessary to bring the sludge level back to that of the previous year.

TABLE V.—*Yearly Solids Balance—Cumulative*

Solids in Imhoff Tanks Accounted for

| | On Basis of Suspended Solids Removal | On Basis of Total Solids Removal |
|---|---|---|
| | 1933 | |
| Dry Solids Deposited (lb.) | 33,033,000 | 36,944,000 |
| Dry Solids Withdrawn (lb.) | 25,533,000 | 25,533,000 |
| Balance (lb.) | 7,500,000 | 11,411,000 |
| Dry Solids Still in Tanks (lb.) | 5,284,000 | 5,284,000 |
| Dry Solids Destroyed (lb.) | 2,216,000 | 6,127,000 |
| Per Cent Destroyed | 6.7 | 16.6 |
| | 1934 | |
| Dry Solids Deposited (lb.) | 43,240,000 | 49,827,000 |
| Dry Solids Withdrawn (lb.) | 32,707,000 | 32,707,000 |
| Balance (lb.) | 10,533,000 | 17,120,000 |
| Dry Solids Still in Tanks (lb.) | 4,244,000 | 4,244,000 |
| Dry Solids Destroyed (lb.) | 6,289,000 | 12,876,000 |
| Per Cent Destroyed | 14.5 | 25.8 |
| | 1935 | |
| Dry Solids Deposited (lb.) | 53,285,000 | 60,623,000 |
| Dry Solids Withdrawn (lb.) | 41,681,000 | 41,681,000 |
| Balance (lb.) | 11,604,000 | 18,942,000 |
| Dry Solids Still in Tanks (lb.) | 3,638,000 | 3,638,000 |
| Dry Solids Destroyed (lb.) | 7,966,000 | 15,304,000 |
| Per Cent Destroyed | 14.9 | 25.2 |
| | 1936 | |
| Dry Solids Deposited (lb.) | 61,517,000 | 71,104,000 |
| Dry Solids Withdrawn (lb.) | 50,559,000 | 50,559,000 |
| Balance (lb.) | 10,958,000 | 20,545,000 |
| Dry Solids Still in Tanks (lb.) | 3,118,000 | 3,118,000 |
| Dry Solids Destroyed (lb.) | 7,840,000 | 17,427,000 |
| Per Cent Destroyed | 12.7 | 24.5 |
| | 1937 | |
| Dry Solids Deposited (lb.) | 68,316,000 | 80,024,000 |
| Dry Solids Withdrawn (lb.) | 56,955,000 | 56,955,000 |
| Balance (lb.) | 11,361,000 | 23,069,000 |
| Dry Solids Still in Tanks (lb.) | 4,114,000 | 4,114,000 |
| Dry Solids Destroyed (lb.) | 7,247,000 | 18,955,000 |
| Per Cent Destroyed | 10.6 | 23.7 |

solids. There appears to be no theoretical justification to suppose that these conversions should or could take place.

6. It appears to make a difference as to the manner in which the volatile content of sewage solids is determined. It can either be determined on the daily composite samples for total solids or suspended solids, or on the sample collected by the method of suspending a bucket either in the flow channel slot of the Imhoff tank or just below the influent slot. On the basis of the data in Table I the average volatile content of the total solids in raw sewage is 46 per cent. The cu-

TABLE VI.—*Southerly Sewage Treatment Plant*

| Year | Total Flow in M.G. | | Total Solids in P.p.m. | | | | Suspended Solids in P.p.m. | | | | Volatile Matter, Per Cent | | | Digested Sludge Pumped | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Imhoff Tanks | Humus Tanks | Raw | Set. | Fil. | Fin. | Raw | Set. | Fil. | Fin. | Fresh Solids | Humus Tank Sludge | Dig. Sludge | Cubic Yards | Sp. Gr. | Per Cent Moisture |
| 1929 | 2,462.2 | 1,085.9 | 851 | 688 | 655 | 632 | 242 | 113 | 76 | 57 | — | — | — | 4,800 | 1.03 | 88.0 |
| 1930 | 3,231.9 | 1,996.5 | 678 | 573 | 500 | 489 | 184 | 93 | 39 | 28 | 72.1 | 51.6 | 39.5 | 10,572 | 1.03 | 85.8 |
| 1931 | 4,352.9 | 3,985.7 | 649 | 557 | 504 | 492 | 188 | 93 | 47 | 33 | 69.3 | 53.6 | 39.5 | 24,427 | 1.03 | 87.2 |
| 1932 | 7,463.8 | 4,291.9 | 756 | 596 | 549 | 528 | 253 | 105 | 67 | 45 | 70.2 | 58.3 | 39.5 | 38,871 | 1.04 | 89.7 |
| 1933 | 7,346.0 | 5,597.2 | 921 | 696 | 649 | 614 | 312 | 121 | 88 | 57 | 68.3 | 55.0 | 44.2 | 65,409 | 1.03 | 91.6 |
| 1934 | 7,428.7 | 4,682.1 | 839 | 670 | 604 | 574 | 251 | 110 | 85 | 47 | 70.8 | 60.4 | 45.2 | 50,507 | 1.03 | 91.8 |
| 1935 | 7,355.0 | 6,029.0 | 772 | 613 | 594 | 573 | 248 | 107 | 71 | 43 | 68.3 | 51.4 | 44.3 | 55,706 | 1.03 | 90.7 |
| 1936 | 7,403.7 | 6,145.9 | 710 | 555 | 539 | 521 | 208 | 82 | 41 | 32 | 69.3 | 55.0 | 42.4 | 55,708 | 1.03 | 90.8 |
| 1937 | 7,488.3 | — | 759 | 616 | — | — | 228 | 119 | — | — | 66.3 | — | 41.6 | 42,360 | 1.02 | 91.2 |

mulative solids treatment, on the basis of total solids, gave a reduction in total solids of about 23 per cent, which would indicate about a 50 per cent destruction of volatile matter. This appears to be a reasonable figure.

7. Another source of error (one present in the data presented) is in the mathematical computations of the given data. The average monthly solids, suspended and total, are determined by adding the individual solids determinations and dividing by their number. Average flows are determined the same way. The solids depositions are then determined on the basis of these average figures. If some of the flows are abnormal the average results will not be precise. Strictly speaking, each day's solids deposition should be computed separately or each day's solids determinations weighted, when using monthly averages. In compiling the yearly report the monthly averages are averaged to give the yearly average. In this way the same error is again committed. For really precise computational work either median values or weighted averages should be used.

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# THE SEWERAGE OF DELHI

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Delhi, the Imperial Capital of India, has, through the ages, been the seat of government of numerous dynasties. The present city of Delhi, enclosed by massive walls, a great part of which are still standing, was built by the Moghul Emperor, Shahjahan, in 1638–1666. With the British occupation, a residential area, known as the Civil Lines, developed to the north of the city while the latter expanded beyond its original walls. Such sewers as existed discharged, without treatment, on to a large farm to the south of the city walls and such liquid as the farm would not absorb overflowed to the river Jumna, on the right bank of which Delhi is situated.

With the inception of New Delhi, the present Imperial Capital, immediately to the south of the city, the abandonment of the old sewage farm was essential and so, included in the project of 1913 for the new capital, which is sewered throughout, were trunk sewers, which carry the sewage from the city through New Delhi and discharge, with the New Delhi sewers, by pumping, on to a sewage farm of 1250 acres at Kilokri. Delhi city is sewered on the combined system while New Delhi has a separate system of storm water sewers running direct to the river. Even in New Delhi, however, rain water finds its way into the foul water sewers. Adequate provision of storm overflows exists.

In designing the scheme it was estimated that the population served would rise to 418,000 by 1955 and that a sewage flow of 8,360,000 Imperial gallons (or 20 gallons per head) daily might, by that date, be expected. Arising from the construction of the new capital however, the population has increased beyond all expectations while the consumption of water per head of population has exceeded the original estimate. The population had reached 416,000 by 1933 and it is estimated now at over 550,000 while the hot weather water demand has risen to over 18 m.g.d. Successive extensions to the waterworks brought the capacity of the latter up to 21 m.g.d. in 1936 and further extensions to increase the capacity to 28 m.g.d. are about to start.

*Proposals for Enlarging.*—In the latter part of 1935, when the writer arrived in Delhi, the sewage farm had become waterlogged and, on account of mosquito breeding and its nearness to New Delhi, had become a menace to public health. Furthermore, on account of the inadequacy of the sewage pumping plant, sewage was heading up the main outfall and was overflowing through storm water outlets into open storm water drains in the urban area. The situation was most serious and plans and estimates for a complete scheme of remodelling were ready early in 1936. Construction started at the end of that year. The works came into full operation September 1, 1938.

*New Works.*—The new works contemplate a population of 750,000

by 1955 with a dry weather sewage flow of 24 m.g.d. and are capable of dealing with three times this flow at times of rain. All storm water in excess of three times dry weather flow passes direct to the river Jumna which, in the rainy season, is in high flood and dilution is ample.

The new works comprise:

1. The remodelling of the storm overflows.
2. The duplication of the outfall.
3. Reconstruction and enlarging of the screening, detritus handling, and pumping plants.
4. The construction of a new duct or sewer from the point of discharge of the pumps to the new disposal works.
5. An activated sludge, surface aeration, purification plant with ancillary works.

*Outfalls.*—The original outfall sewer is a brick barrel, 66 in. in diameter and capable of carrying 36 m.g.d. This has been duplicated by a second sewer of the same size which, in its upper reaches, is of brick construction. Due, however, to the waterlogging which has occurred over the sewage farm, this sewer in its lower lengths is several feet below water level and here it is constructed of reinforced concrete. The use of aluminous cement for this sewer was considered but its behaviour under Indian climatic conditions being open to doubt, the idea was abandoned. A good watertight job has been obtained. The outfall sewers commence and terminate in junction chambers where the flow can be controlled by 66 inch, cast iron penstocks. At the lower end the junction chamber is joined to the screening plant.

*Screening Plant.*—The new screening chamber, which had to be built round the original works at Kilokri without stopping continuity of flow, and with a floor 15 ft. below standing water level, is over 40 ft. diameter and contains two vertical screens 12 ft. by 8 ft. while, in the centre space occupied by the old outfall sewer before reconstruction, there is room for a third screen should this be required. Screen bars have a clear spacing of ¾ in. and are cleaned by grab type rakes with no moving parts permanently submerged in the sewage. The operation of the screen rakes is automatic and the screenings are discharged on to a moving belt and conveyed to tip wagons whence they are removed for burial or incineration. Due to the gross misuse of the sewers by an illiterate population, the amount of floating matter in Indian sewage is far in excess of that found under European (and, presumably, American) conditions.

*Detritus Removal.*—Immediately beyond the screens are two curved weirs and a horizontal slab cutwater which divert the lower strata of the sewage, which contain the road grit, into two detritus separating wells, while permitting the upper strata to pass straight on to the suction channel feeding the pumps. On entering the detritus wells the sewage is deflected downwards and then, rising upwards, it drops its heavier, suspended matter. The liquid with the light organic matter still in suspension passes over radial weirs and back into the main

flow. A weighted plate, hanging on a horizontal axis, across the sewage channels causes a slight heading up on the upstream face of the weirs to which reference has been made and this is sufficient to force a flow through the detritus wells. The wells have hopper bottoms and from time to time the grit is removed by a gravel pump in a column of water to a separator above ground level (Fig. 1). The water used for carrying the detritus is lifted to such height that it can pass into the rising main and so no head is lost. Experimental work is still in progress with a view to ascertaining what velocities through these wells give optimum conditions of efficiency.

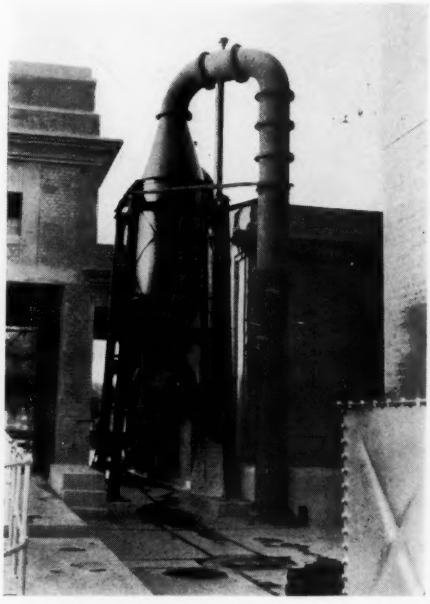

FIG. 1.—Grit separator, Delhi.

*Pumping Plant.*—The original pumping plant comprised three Worthington Simpson pumps, each with a duty of 12 m.g.d. against a maximum head of 60 feet. Steam is supplied by three Babcock and Wilcox watertube boilers. One boiler can supply steam for one engine. As usually one boiler is undergoing periodical cleaning only two pump units are available for normal running. The capacity of the plant is thus 24 m.g.d. or about three times the original contemplated maximum dry weather flow. As these pumps have many years of useful life, the levels of the new disposal works were so arranged that the head of the gravity sewer running onwards from the point of discharge of the pump rising mains is at the same level as the point of original discharge of the pumps.

The new works being designed to deal with 24 m.g.d. dry weather flow or three times this amount at times of rain, additional pumps were

required and a new pumping station has been constructed. In this pumping station, six electrically operated units, each of 12 m.g.d. capacity, will eventually be located. At present three units have been installed (Fig. 2). Each pump is direct coupled with an electric motor of 220 horsepower. The pump glands are sealed by filtered water supplied from a separate pumping system. Renewable eye and neck rings to the impellers enable the pump efficiencies to be economically maintained. These rings are subject to considerable wear and experiments with different types of rings are being carried out.

FIG. 2.—Electric pumping plant, Delhi.

The pump suctions are open ended and the pumps are primed by creating a vacuum in the pump body. Electrically operated exhausters are provided for this purpose. The exhausted air is discharged into the outside atmosphere through a ventilating shaft. The interior of the pumping station is completely free from odor.

The pumps discharge into a 44 in. rising main and the flow therein is recorded by an " Electroflo " venturi meter. The venturi recorders are mounted alongside the switchboard. The old steam pumps discharge into a similar rising main.

The pump makers' guarantees provided for an overall efficiency of 70 per cent working at a head of 57 feet while on official tests an efficiency of 76 per cent was obtained.

The pumping station building also contains the works offices, a large store and a workshop fully equipped for carrying out all running repairs. There is also an electrician's workshop, forge and small foundry.

*Duct.*—The rising mains are each about 800 ft. long and discharge into a junction well at the head of the so-called gravity duct running to the disposal works. This duct is about 4 miles long and is of "U" section, 6 ft. 3 in. wide and 7 ft. deep. Ventilation shafts are provided about every 800 ft. and manholes every 400 feet.

*Disposal Works.*—Investigations showed that, owing to the level nature of the country, a gravity flow the whole way to any disposal works was impossible and so, in selecting the site for the purification plant it was desirable to so locate the latter that it could be commanded by gravity from the point of discharge of the original pumping plant. This has been done and use has also been made of rock strata underlying the site to give a solid foundation for the deep sedimentation tanks. There is no water at the disposal works site, therefore a 4 in. water main had to be laid before work could commence. This line forms part of the finished scheme.

On reaching the disposal works the sewage first passes through a flume recorder which, in addition to giving a local record of the momentary flow, also transmits electrically a flow record to the office on the works. Similar recorders are fitted to the effluent and return sludge channels.

FIG. 3.—General view of Simplex surface aeration plant at Delhi. Final sedimentation banks in the foreground.

The purification plant (Fig. 3), as at present built, can deal with a dry weather flow of 18 m.g.d. but has been designed so that it can be readily extended, to deal with 24 m.g.d. The purification process is

divided into three stages: preliminary sedimentation (1½ hr. detention), aeration (12 hr.), and final sedimentation (6 hr.). The plant is divided, longitudinally, into three sections and the concrete retaining walls have been designed to permit any one section being dewatered without interfering with the operation of the rest of the plant. The outer wall at the south end has been designed as a pressure retaining wall so that it can resist water pressure when, at some later date, an extra 6 m.g.d. section is added at this end of the plant. Labor and cement in India are cheap, stone is available on the site, while sand was nearby. Reinforced concrete construction was, therefore, used wherever possible and it is believed that few activated sludge plants have such a large proportion of this class of construction. Maintenance costs on the structure will, therefore, be negligible.

After passing the inflow recorder the sewage enters a feed channel running across the full width of the plant and into this channel the surplus activated sludge of the plant is discharged. Through 24 in. valves in the floor of this channel the sewage runs to the twelve preliminary settling tanks, each 30 ft. square, about 37 ft. deep and with hopper bottoms. Deflector boxes prevent the incoming sewage disturbing the surface of the liquor in the tanks. The clarified sewage passes to a balancing channel while the mixed sludge, collecting in the hopper bottoms, is run off, from time to time, under hydrostatic pressure through 6-in. drawoff pipes to a sludge channel and thence to the drying beds, which will be described later.

The aeration tanks are fed from the balancing channel, and at the inlet end of these tanks the activated sludge is turned into the incoming sewage. The aeration tanks are formed of 108 pockets, each 30 ft. square and in the centre of each pocket is an uptake tube of reinforced concrete. At the top of each of these tubes is a paddle wheel revolving on a vertical shaft, co-axial with the uptake tube and these paddles draw the contents of the pocket up the tube and throw them, in a finely divided state, over the surface of the tank liquor. Suitable baffle walls are provided, so that the sewage, in its passage through these tanks, follows a sinuous course and obtains the maximum amount of aeration.

The aeration paddles (cones) are suspended from gearboxes mounted on long reinforced concrete bridges. Each gearbox contains a bevel drive with machine-cut gears and pump lubrication and is also provided with a clutch whereby any cone can be thrown out of operation without disturbing the running of the rest of the plant. Flange couplings at the ends of each gear-box admit of its removal for repairs, and short lengths of shafting, with flanges, are carried as spares to admit of a given line of cones being kept running with a minimum of stoppage. Each bridge spans nine pockets and the lines of cones are driven by 36 horsepower motors mounted on a cross bridge spanning the aeration tanks. Expansion joints, both in the concrete and in the shafting, prevent any temperature stresses being transmitted to the machinery. Air temperatures at Delhi vary from a few degrees below

freezing on a winter night to 140° F. in the heat of summer. Expansion movements on a 270 ft. bridge are, therefore, considerable. Ball bearings are used throughout and grease nipple lubrication is employed.

The motors, which drive the shafting through chain drives running in oil baths, are of the double squirrel cage type, totally enclosed for outside operation. Each motor has, in addition, a hinged sheet metal cover, painted aluminum, to reflect back as much heat as possible.

At the outlet end of the aeration tanks are adjustable weirs, whereby the level of the liquid in the tanks, and hence the cone submergence, may be varied within limits. The object of the process is, naturally, to produce an effluent complying with the required standards, with a minimum consumption of power. All cones, at present, run at the same speed and with the same submergence. Experiments are, however, about to be carried out with the first two or three cones in each line rather more submerged than the others. This will give greater aeration at the point where greatest aeration is required. The overflow weirs communicate with a second balancing channel from which the final settling tanks are fed. There are 48 of these tanks, which are of the same design as the preliminary settling tanks. The clear effluent is run off through steel overflow channels to the main effluent channel. A flume, recording the flow, is incorporated in this channel.

The effluent has to comply with the British Royal Commission Standards, namely:

The suspended solids must not exceed 3 parts per 100,000.
The albuminoid ammonia figure must not exceed 0.2 per 100,000.
The five-day B.O.D. figure must not exceed 2.0 parts per 100,000.

Furthermore, the makers of the plant, under penalty, guaranteed that with the normal Delhi sewage these figures would be obtained with a power consumption not exceeding 450 units of electricity per million gallons treated. Official acceptance test figures, taken over a nine day test were:

| | | | |
|---|---|---|---|
| Suspended Solids, parts per 100,000 | Max.: | 1.30 | |
| | Min.: | .60 | Mean 0.95 |
| Albuminoid Ammonia | Max.: | .14 | |
| | Min.: | .12 | Mean 0.13 |
| Five-day B.O.D. Figure | Max.: | 1.20 | |
| | Min.: | .74 | Mean 1.00 |

Experiments are now being carried out checking power consumption against B.O.D. reduction. By American standards the consumption of water in Delhi is low and hence the sewage is strong, while, the distance to the disposal works being long, septic action in the sewage has taken place to a considerable extent.

*Power.*—A 6600 volt three-phase overhead transmission line, seven miles long, runs from the New Delhi power station to the disposal works, with a branch to the Kilokri pumping station. The pumping station can also be fed by an entirely independent line.

The transformers and switchgear at the disposal works are located in a building immediately alongside the plant and both on the high tension and on the low tension sides the installation can deal with the requirements of the plant when extended to deal with 24 million gallons daily. When the extensions to the works take place the spare panels of the low tension switchboard can be connected without interfering with the operation of the plant. All circuits are separately metered and all cables are laid underground. The purification plant and the sludge drying beds are illuminated at night by large floodlights. Power and light plugs at convenient points all over the plant permit the easy connection of inspection lamps and temporary plant. Current is supplied at a through rate of 0.55 anna (1.10 cents) per unit.

*Sludge Return.*—The activated sludge settled in the final settling tanks is removed periodically by "Ames Crosta" automatic de-sludging gear to the sludge draw-off channel whence it is lifted to a flume in which it returns to the incoming sewage or to the inlets of the aeration tanks. A Lea Recorder is incorporated into this flume. There are four return sludge pumps of the horizontal split casing type and the glands are sealed by filtered water.

*Sludge Disposal.*—The mixed sludge from the preliminary settling tanks is drawn off through 6-in. piping to a sludge channel whence it runs through a spun reinforced concrete pipe to the sludge drying beds. These are situated about two-thirds of a mile from the main plant on lower ground and the sludge can be run on to the beds by gravity. The beds are 3 ft. 6 in. deep, of graded stone and sand, and measure 700 by 500 feet. They are divided by concrete roads and tramway tracks into six subsidiary beds and the sludge is fed to these through reinforced concrete channels. The sludge dries partly by evaporation and partly by draining. There is a growing demand for the sludge for use as manure while the surplus is removed in tip wagons to an adjoining depression. The liquor which drains through the beds is received on a concrete floor and runs into a collecting channel, whence it is pumped back into the incoming sewage. The pumps for this duty are automatically controlled by float operated switches.

*Digestion.*—The original project, prepared by the writer, contemplated sludge digestion and the possible use of sludge gas for power purposes. During the hot weather, despite all precautions, fly breeding will start on these beds and sooner or later digestion, deferred in the first instance to reduce cost, will be adopted. The works are well away from urban areas but in a tropical country any process which encourages breeding of flies is to be deprecated.

*Laboratory Control.*—The works have a fully equipped laboratory while, in the chemist's office are electrically operated recorders showing the inlet, outlet and return sludge flows. In addition to the record of instantaneous flow, these recorders also have integrators and weekly charts. Samples of effluent and aeration tank liquor are taken every two hours throughout the day and night and an effluent well up to requirements is being maintained.

*Costs.*—Figures of cost given below may be of interest. Much of the machinery had to be imported from abroad and a carefully prepared construction programme was necessary to enable the works to be completed within 21 months. Costs of the various sections were:

| *Section* | *Rupees* | *Dollars* |
|---|---|---|
| Outfall sewer | 400,000 | 110,000 |
| Screening and detritus plants | 250,000 | 70,000 |
| Pumping station, plant and rising main | 380,000 | 105,000 |
| Gravity duct | 420,000 | 115,000 |
| Disposal works, including residential buildings, office, laboratory and effluent channel | 2,450,000 | 680,000 |
| High tension electric line | 70,000 | 20,000 |
| Works water supply | 35,000 | 10,000 |

The plant has not been in full operation for a year but operation costs are working out somewhat lower than estimated. Estimated annual running costs, allowing for repairs, operation and depreciation fund contributions are Rs. 350,000 (Dollars 100,000). The plant is administered by the Delhi Joint Water and Sewage Board to whom it was handed over free of debt charges. This undertaking controls the bulk supply of filtered water and the removal of all sewage from the Delhi urban area.

*Sale of By-Products.*—A channel nearly two miles long runs from the purification plant to the River Jumna. About 3000 acres of land are, however, commanded by gravity from this channel and irrigation is being rapidly developed. Charges for effluent are 25 per cent above those of the ordinary irrigation canals. A further 1100 acres is to be irrigated by pumping. In its route to the river, the effluent channel passes over the Agra Canal and arrangements have been made for discharging up to 12 cusecs into this channel. Very little water will, therefore, reach the river, except at times of rain. At such periods the river is in heavy flood and a very heavy dilution is obtained. At certain periods of the year the flow in the river is very low and risk to public health might occur if large quantities of effluent were turned into the river at such times. A gaseous chlorine plant has, therefore, been provided and this can give a dose of up to 3 p.p.m. of chlorine to the sewage. This plant will only be operated for a few months in the year and, as irrigation develops, to a decreasing amount.

Sales of sludge are developing slowly but it is anticipated that once the results on one crop have been seen, the demand will rapidly rise.

# Stream Pollution

## IMPOUNDING RESERVOIR IN STREAM PURIFICATION WITH RESPECT TO SLUDGE BANK FORMATION *

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A major factor in stream pollution problems is the extent and character of sludge deposits, which form to more or less extent in practically all cases where sewage dilution is practiced. Interest in this phase of the problem lies principally in (1) the quantity of sludge deposited, (2) its character, with respect to nuisances and odors, and (3) the oxygen demand created on the diluting medium.

Data on the subject published in this country have been provided by the laboratory work of Baity,[1] Streeter,[2] Rudolfs,[3] and Fair and Moore [4] in which sludges were studied under controlled conditions, and by the investigations of Rudolfs [5] on the Connecticut River under natural river conditions.

It is hoped that the information given in this paper will add to the knowledge by giving some characteristics of sludge bank formation under various conditions which affect the natural quantity, composition and changes of sludge deposits in a quiescent body of water receiving the effluent from a trickling filter plant.

The situation consists of a small stream receiving a comparatively large volume of tricking filter effluent, which passes through an impounding reservoir of 1 to 5 days detention period. Previous studies [7] on this same location have been given by one of the authors to show (1) the effect of the reservoir on the reduction in biochemical oxygen demand of the stream-sewage effluent mixture, (2) reduction of *B. coli*, (3) reaeration by the dam overfall, (4) dissolved oxygen depletion in the reservoir and (5) coefficients of deoxygenation and reaeration. Results were obtained under both winter and summer conditions.

While the body of water showed effective purifying aid to the stream and furnished decided advantages, it was still a question as to what disadvantages might arise due to long-term accumulation of sludge deposits, especially with respect to the rate of accumulation of sludge and to the character of the material which it might ultimately be necessary to remove. Subsequent studies have now been made with respect to the second phase, *i.e.* the extent and character of sludge bank formation in the same reservoir.

The results of studies on this phase of the situation are given in this paper.

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## General Situation

A plan of the reservoir in relation to stream inlets and outlet and sewage plant outfall is shown in Fig. 1. The reservoir has an approximate area of 225,000 sq. ft. and a capacity of 15,000,000 gallons. Average stream flow through the reservoir was 8.0 c.f.s. with a maximum of 27.0 c.f.s. and a minimum of 4.7 c.f.s. The sewage flow, included in the previous figures, was 1.46 c.f.s.

The reservoir has been receiving the treated sewage and stream water mixture for the past eight years. During the first year of this period the sewage effluent was introduced in stream *A* above the reservoir entrance in the location shown in Fig. 1. During the succeeding

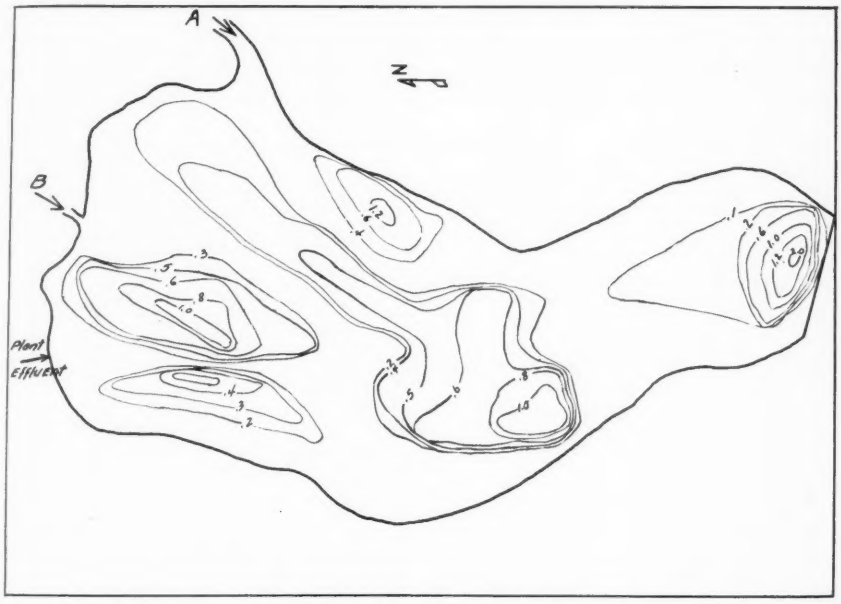


Fig. 1.—Quantity of sludge-sediment accumulated in 8 years operation.

five-year period the sewage was introduced into the pond at the location shown by the plant outfall, and the stream water entered through a new channel located at *B*. In the last two years the stream water has been separated from the sewage and re-diverted to the entrance at *A*, the sewage outfall remaining in the same location.

The sewage effluent is from a typical trickling filter operating at standard rates. The plant consists of primary sedimentation, filtration and secondary settling combined with chlorination. The biochemical oxygen demand of the plant effluent varies between 25 and 40 p.p.m. Suspended solids in the effluent have approximately the same range with an average value of 32 p.p.m.

Of particular interest to this study were the character and quantity

of the suspended solids. Analysis of the suspended solids on a centrifuged sample showed the following characteristics:

pH, 6.6
Volatile matter, 69.5 per cent
Centrifuged solids, 8.4 per cent
B.O.D. per gram solids, 274 mg.
B.O.D. per gram vol. solids, 540 mg.
Nitrogen, 4.9 per cent on total sol. basis
Nitrogen, 8.3 per cent on vol. matter basis

Approximately 92,000 lb. or 46 tons of these solids, on the dry basis are introduced into the reservoir each year.

## Results

The investigation has been made and results compiled to show three principal factors in the situation: first, the quantity of sludge accumulated in the form of banks in the pond, second, the character of the material deposited, and third, the oxygen demand of the sludge deposits. Correlations are also made showing the nitrogen changes in the sludge.

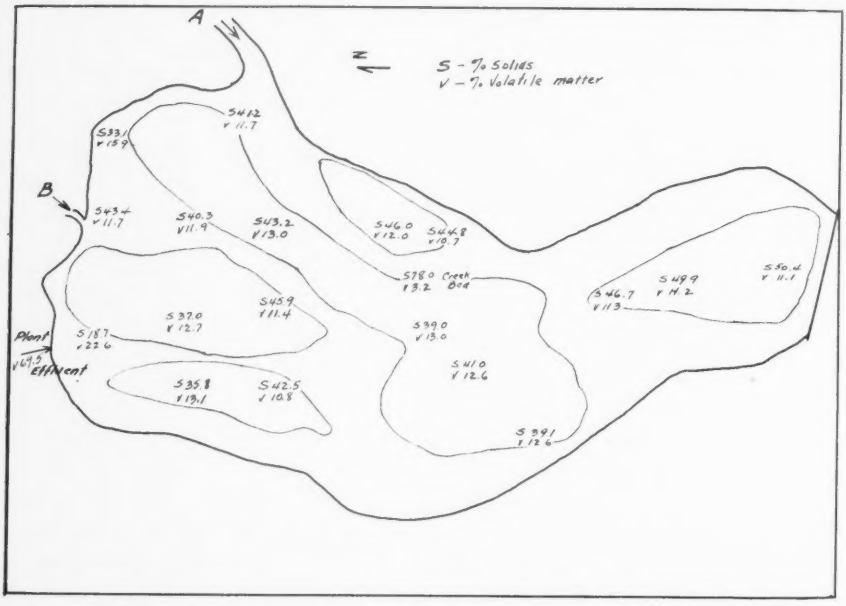


Fig. 2.—Volatile and solids content of sludge-sediment with respect to lateral distribution.

The quantity of sludge accumulated and its lateral distribution over the eight year period are shown in Fig. 1, in the form of a topographical plate of the lake bottom giving depth of sludge deposits in feet. This information was obtained by means of a survey of the bottom before and at the end of the eight-year period. The figures show the depth and conformation of the deposits in feet.

The character of material deposited with respect to solids, volatile

matter, biochemical oxygen demand and nitrogen content is shown in Figs. 2 and 3 and Tables I and II. Table I shows the analysis of the sediment at both transverse and vertical locations in the reservoir. Table II gives the comparative composition of the top and bottom strata of the sediment. Figs. 2 and 3 show the relative composition of the sediment at significant transverse locations.

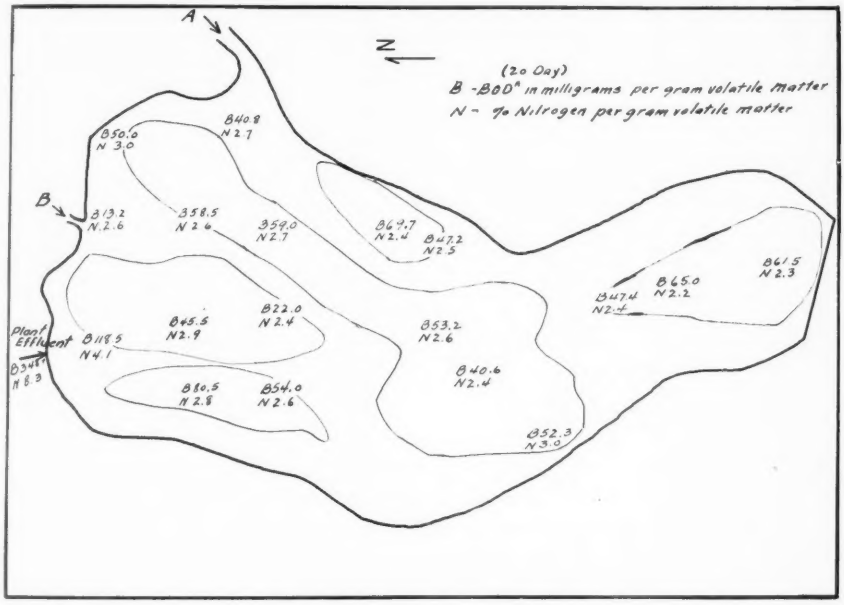


FIG. 3.—Biochemical oxygen demand and nitrogen content of sludge-sediment with respect to lateral distribution.

Samples were collected vertically from the top and bottom of the sediment layer by means of a self-closing sampling device which permitted collection at the selected depth.

Methods of analyses conformed to the A. P. H. A. "Methods of Water and Sewage Analyses" for sludge and sediments.

## DISCUSSION OF RESULTS

*Total Quantity and Distribution of Sediment.*—One of the questions of most practical importance is the rate of accumulation of sludge or sediment in the reservoir. This question is of specific significance in describing the life of a natural basin used as an adjunct to stream purification, with respect to diminishing capacity requirements, and in the prediction of required cleaning intervals.

In this instance there are three major factors contributing to the increase in bottom sediment *i.e.*, (1) silt carried by the stream flow, (2) suspended solids contributed by the sewage plant effluent together with

TABLE I.—*Analysis of Sludge and Sediment Deposit*

| Location | Per Cent Solids | Per Cent Volatile Matter | 20-day B.O.D. in Mg. | | Per Cent Nitrogen | | pH |
|---|---|---|---|---|---|---|---|
| | | | per Gm. Solids | per Gm. Vol. Mat. | Total Solids | Volatile Matter | |
| 1. Top..... | 37.0 | 12.8 | 8.2 | 61.5 | 0.34 | 2.63 | 6.2 |
| Bottom.. | 41.2 | 12.4 | 5.4 | 43.1 | 0.43 | 3.45 | 5.8 |
| 2. Top..... | 33.6 | 13.5 | 5.6 | 40.2 | 0.36 | 2.67 | 6.2 |
| Bottom.. | 48.4 | 11.7 | 4.6 | 41.0 | 0.25 | 2.15 | 5.8 |
| 3. Top..... | 25.6 | 15.0 | 8.1 | 55.0 | 0.47 | 3.19 | 6.4 |
| Bottom.. | 52.5 | 11.0 | 5.5 | 51.5 | 0.23 | 2.10 | 5.9 |
| 4. Top..... | — | — | — | — | — | — | — |
| Bottom.. | — | — | — | — | — | — | — |
| 5. Top..... | 40.9 | 11.0 | 7.3 | 68.5 | 0.29 | 2.67 | 5.9 |
| Bottom.. | 48.8 | 10.5 | 2.7 | 26.0 | 0.25 | 2.42 | 6.3 |
| 6. Top..... | 44.4 | 12.1 | 12.2 | 102.0 | 0.25 | 2.10 | 6.4 |
| Bottom.. | 47.5 | 11.8 | 4.4 | 37.5 | 0.34 | 2.77 | 5.7 |
| 7. Top..... | 48.6 | 11.3 | 4.1 | 36.5 | 0.30 | 2.67 | 6.5 |
| Bottom.. | 52.3 | 11.0 | 9.6 | 86.0 | 0.23 | 2.09 | 6.6 |
| 8. Top..... | 35.8 | 11.8 | 8.4 | 73.0 | 0.32 | 2.74 | 6.0 |
| Bottom.. | 49.2 | 9.8 | 3.5 | 35.0 | 0.25 | 2.54 | 6.5 |
| 9. Top..... | 27.8 | 15.1 | 14.1 | 96.0 | 0.49 | 3.24 | 6.3 |
| Bottom.. | 43.9 | 11.0 | 7.1 | 65.0 | 0.27 | 2.48 | 6.2 |
| 10. Top..... | 10.1 | 29.4 | 50.5 | 174.0 | 1.42 | 4.8 | 6.5 |
| Bottom.. | 27.4 | 15.8 | 10.0 | 63.0 | 0.54 | 3.44 | 6.5 |
| 11. Top..... | 29.8 | 15.5 | 10.6 | 67.0 | 0.47 | 3.08 | 6.6 |
| Bottom.. | 44.2 | 10.0 | 2.4 | 24.0 | 0.28 | 2.77 | 6.5 |
| 12. Top..... | 38.4 | 12.9 | 4.6 | 35.0 | 0.33 | 2.64 | 6.4 |
| Bottom.. | 53.5 | 10.0 | 0.9 | 9.0 | 0.21 | 2.10 | 6.2 |
| 13. Top..... | 34.0 | 14.0 | 10.0 | 72.0 | 0.38 | 2.75 | 6.4 |
| Bottom.. | 42.8 | 11.7 | 5.3 | 46.0 | 0.33 | 2.82 | 6.4 |
| 14. Top..... | 29.9 | 14.6 | 11.2 | 77.0 | 0.43 | 2.96 | 6.6 |
| Bottom.. | 50.7 | 9.2 | 3.7 | 40.0 | 0.22 | 2.34 | 6.1 |
| 15. Top..... | 35.6 | 12.8 | 2.4 | 18.2 | 0.32 | 2.60 | 6.2 |
| Bottom.. | 41.1 | 10.7 | 1.0 | 9.3 | 0.28 | 2.62 | 6.0 |
| 16. Top..... | 19.8 | 20.0 | 17.2 | 88.0 | 0.78 | 3.82 | 6.5 |
| Bottom.. | 46.5 | 11.8 | 1.4 | 12.0 | 0.26 | 2.21 | 6.0 |
| 17. Top..... | 36.1 | 13.0 | 6.3 | 48.5 | 0.37 | 2.86 | 5.9 |
| Bottom.. | 46.4 | 10.5 | 3.5 | 33.1 | 0.28 | 2.64 | 5.8 |
| 18. Top..... | 40.6 | 12.9 | 9.4 | 72.0 | 0.33 | 2.57 | 6.4 |
| Bottom.. | 52.7 | 9.6 | 2.2 | 22.9 | 0.23 | 2.34 | 6.2 |
| 19. Top..... | 49.9 | 11.3 | 3.5 | 31.0 | 0.25 | 2.20 | 6.5 |
| Bottom.. | 49.9 | 11.0 | 10.0 | 99.0 | 0.27 | 2.39 | 6.5 |
| Average. | 40.4 | 12.7 | 7.7 | 54.4 | 0.38 | 2.72 | 6.2 |

colloidal material, some of which may precipitate through the physical, chemical, and biological activities in the diluted mixture and (3) the growth, death and decomposition of reservoir plankton and vegetation. The net results of all three have been quantitatively determined by direct measurement. During the eight-year period the total quantity of sediment added to the reservoir bottom by measurement has been 65,000 cu. ft., or approximately 2,100 tons, with average composition as

TABLE II.—*Comparison of Top and Bottom Sediment*

| Location | Per Cent Solids | Per Cent Volatile Matter | B.O.D. in Mg. | | Per Cent Nitrogen | | pH |
|---|---|---|---|---|---|---|---|
| | | | per Gm. Solids | per Gm. Vol. Mat. | Total Solids | Volatile Matter | |
| Top Maximum | 49.9 | 20.0 | 50.5 | 174.0 | 1.42 | 4.80 | 6.6 |
| Top —Minimum | 10.1 | 11.3 | 2.4 | 18.0 | 0.25 | 2.10 | 5.9 |
| Average | 34.3 | 14.4 | 10.7 | 67.5 | 0.42 | 2.89 | 6.3 |
| Bottom—Maximum | 53.5 | 15.8 | 10.0 | 99.0 | 54.0 | 3.45 | 6.6 |
| Bottom—Minimum | 27.4 | 9.2 | 0.9 | 9.0 | 21.0 | 2.09 | 5.7 |
| Average | 46.6 | 11.1 | 4.6 | 41.3 | 0.29 | 2.53 | 6.2 |

follows:

| | |
|---|---|
| Total Solids | = 40.4 per cent |
| Volatile Matter | = 12.7 per cent |
| B.O.D. per gram Solids | = 7.7 mg. |
| B.O.D. per gram Vol. Solids | = 54.4 mg. |
| Nitrogen, Total Solids | = 0.38 per cent |
| Nitrogen, Vol. Matter | = 2.72 per cent |
| pH | = 6.2 per cent |

This indicates that, quantitatively speaking, the theoretical natural effective life of the reservoir to be expected under the present loading is approximately 31 years. On a basis relative to plant capacities, approximately 22 cu. ft. of reservoir capacity per ton of solids per year is needed, including accumulation due to silt and vegetation. The rate of accumulation of total sediment is about 3 per cent per year. This does not take into consideration however, the possible prolongation of the life due to decreasing sedimentation efficiency with decreasing capacity, which would eventually become an effective factor.

It is also of interest to consider the quantity of sediment that has been contributed to the composite bottom sediment by the sewage solids. During the eight-year period the quantity of suspended solids introduced in the pond, as estimated from the sewage plant effluent analysis, was 736,000 pounds on a dry solids basis. Investigations show approximately 95 per cent retention of solids in the reservoir. With this efficiency 699,000 pounds of dry solids would be added to the bottom sediment by the sewage. Destruction of volatile matter in amount indicated by the data would reduce this to 277,000 pounds.

With an average solids content of 40 per cent, the maximum quantity of solids contributed to the bottom sediment by the sewage has been 693,000 pounds or 11,000 cu. ft. on a wet basis. The quantity of bottom sediment actually accumulated has been 65,000 cu. ft. Thus only 17 per cent of the sediment accumulated has been due to the sludge from the plant and 83 per cent due to silt and decaying vegetation. On a unit working basis, 3.9 cu. ft. of lake capacity is therefore needed per

ton of sewage solids per year, exclusive of natural silt and sediment carried by the stream.

*Character of Sediment—Physical and Chemical.*—A second question of practical importance is the nature of the sediment. As shown in Table I the composite material contained 40.4 per cent solids, with a volatile matter content of 12.7 per cent. The 20-day B.O.D. of the material on a total solids basis was relatively low (7.7 mg. per gram of total solids). The B.O.D. per gram of volatile solids was 54.4 milligrams. Nitrogen on total basis was 0.38 per cent and on a volatile basis 2.72 per cent. The pH of the composite material was 6.2.

For purposes of determining the relative state of decomposition of the lake deposits, analyses were made on the sediment from two other sources in the vicinity representing natural conditions without sewage solids contamination. Samples were collected from a small pond located in the stream just above the lake under consideration. The other location was taken from a field in the immediate vicinity. As compared to the lake deposits and suspended solids in the plant effluent these locations gave:

| | Per Cent | | Mg. B.O.D. (20 day) | | Per Cent Nitrogen | | pH |
|---|---|---|---|---|---|---|---|
| | Solids | Vol. Mat. | per Gm. Solids | per Gm. Vol. Mat. | Total Sol. | Vol. Mat. | |
| Lake deposit (avg.) | 40.4 | 12.7 | 7.7 | 54.4 | 0.38 | 2.7 | 6.2 |
| Thompsons Pond (above lake) | 49.5 | 9.5 | 1.8 | 19.3 | 0.25 | 2.6 | 6.1 |
| Soil in vicinity | 78.6 | 5.0 | 0.2 | 4.5 | 0.12 | 2.5 | 6.2 |
| Susp. sol. (sew. eff.) | 91.6* | 69.5 | 370 | 540 | 4.9 | 8.3 | 6.6 |

* Centrifuged.

This shows that with respect to the indices used, the average analysis of the material in the lake was not far from that deposited under the natural unpolluted conditions of Thompsons pond, with the exception of the B.O.D., which is materially higher than that of the material deposited under nonpollutional conditions.

The extent of decomposition of the sludge from the plant is also indicated by the comparison between the analyses of the suspended solids in the sewage effluent as compared with the analyses of the lake bottom deposits in the above table.

The composition of the sludge with respect to lateral distribution is shown in Fig. 2. It would seem logical to assume that at greater distances from the source of pollution the material would show increasing characteristics of decomposition. A slight tendency is shown in this respect over the broad area of the lake. Significant differences, though, are limited to a relatively small area around the plant outfall. The character of the sediment with respect to the state of decomposition changes rapidly for a distance of 200 feet from the outfall, with 94 per

cent destruction of volatile matter. At this point the characteristics are approximately the same as other more extended portions of the area.

It was also thought of interest to observe the differences in decomposition of the more finely divided or precipitated colloidal material which might be carried to the farthest parts of the lake. The data indicate that this material was practically the same as the heavier, coarser material settled nearer the outfall.

With regard to vertical distribution, Table II shows more significant differences. The bottom layer of the deposited sediment shows a distinctly higher stage of decomposition than the top strata, from the viewpoint of all indices used. However, the differences are not proportionate to the age of the deposit. The average age of the bottom layer represented by the sample is estimated at 6 years and that of the top layer at 2 years.

*Bacterial and Microscopic Aspects.*—Microscopic observations and bacterial counts were made on the top and bottom sediments.

Active protozoan population of the material, with the exception of a few sewage forms in the area surrounding the sewage outfall, was practically absent. The sediment contained numerous shells of diatomaceous forms, which had apparently settled to the lake bottom from the overlying water, but otherwise was practically barren.

The bacterial population of the sediment was likewise relatively low. In fresh material immediately surrounding the sewage outfall, the 48 hour plate count was 310,000 per gram of material in the top layer of sediment and 380,000 per gram in the bottom strata. In the more aged sediment the counts were 160,000 per gram of sediment in both the top and bottom layers.

On the basis of organic material, the bacterial counts in the fresher material near the outfall were 10,500,000 and 8,800,000 per gram of organic material in the top and bottom layers respectively. In the older material the counts were 3,300,000 per gram of organic material in both the top and bottom layers. The bacterial examinations indicate that the stationary population of the bottom sediment was about 3,000,000 bacteria per gm. of volatile material, which represents approximately 30 per cent of the population of the more freshly introduced solids. This ultimate figure is somewhat less than that given for solids. Waksman [8] indicates counts of from 320,000 to 500,000 bacteria per gram for sandy soils and 360,000 to 600,000 per gram for loamy soils. On the basis of organic material, this would amount to approximately 8,000,000 to 15,000,000 bacteria per gram for the soils as against 3,300,00 per gram of organic material in the lake sediment. Total plate counts in fresh solids and actively digesting sludge run from 10 to 20 billion per gram of volatile material.

## General Discussion

*Impounded Waters as Sewage Treatment Unit.*—A general survey of the foregoing data and references would indicate that impounded

bodies of water have a function in the process of sewage purification, especially where natural conditions are available for such use, or where a lake can be artificially created at moderate cost. Such reservoirs with suitable organic loadings appear to be capable of adequately treating both the sewage liquor and suspended solids; the former aerobically, and the latter by a combination of both aerobic and anaerobic processes. They would appear to be especially valuable as a final adjunct to sewage purification processes, under situations where a very high quality of stream water is desired, thus requiring the oxidation of relatively little remaining pollution, which is hard to obtain economically with artificial sewage plant processes.

This function of lakes is illustrated with respect to sewage liquor and suspended solids. With sufficient natural diluting water the dissolved and colloidal organic matter in the sewage is readily oxidized, destruction of *B. coli* is positive, and settleable solids of sludge forming characteristics are rapidly decomposed.

During the passage through the pond, B.O.D. reductions of the polluted water amounted to 66.5 per cent during the summer and 52.5 per cent during the winter. *B. coli* were reduced 76 per cent during the summer and 40 per cent during the winter. Suspended solids of sludge-forming characteristics were decomposed, without nuisance, with 94 per cent destruction in volatile matter and a reduction in B.O.D. of approximately 90 per cent on a volatile matter basis. Reduction in suspended solids amounted to 95 per cent.

These results were secured with a loading equivalent to a rate of application of sewage amounting to 190,000 gallons of trickling filter effluent per acre of lake area per day. Rates of application customarily used on sand filters receiving similarly treated sewage are from 250,000 to 300,000 gallons per acre per day. Under naturally favorable conditions, the equivalent cost of construction may be relatively small. This is especially true since shallow areas would be preferable to deep ones for maximum purification rates. Greatest surface area for oxygen absorption and greatest biological concentration per unit volume of water is secured in the shallower areas.

Operation of an impounded water under natural conditions might allow potential nuisances to exist in two ways; first, odors arising from depletion of oxygen in the water and second, nuisances accompanying the removal of sludge from the area, which might eventually be required in order to maintain reservoir or lake capacities.

The data in the present study indicate that, at least as far as sewage treatment is concerned, odors or nuisances have not occurred. The dissolved oxygen content of the lake effluent averaged 7.4 p.p.m. during the winter period and 2.2 p.p.m. during the more critical summer period, thus allowing ample margin for prevention of odors. Experiences also indicated that much lower limits of oxygen could be tolerated without nuisance. At one of the most critical hot weather drought periods experienced in the operation of the pond, the dissolved oxygen fell as low as 0.5 p.p.m., with no attendant odors or nuisance. With

respect to nuisances attending the possible necessity for removal of sludge, the data indicate that these troubles should be much less than those encountered with sludge from the most efficient digestion processes. Destruction of volatile matter of the sludge which would have to be removed amounted to about 94 per cent under the natural aerobic-anaerobic processes of the lake unit, as against an expected reduction of 50 to 60 per cent in digestion tanks. Volatile matter content varied between 11 and 15 per cent, as against 45 to 55 per cent for sewage sludge. Biochemical oxygen demand on both total and volatile solids basis was likewise relatively low in the sludge from the impounded waters.

Maintenance problems of the reservoir are practically negligible. The vigorous growth of weeds and plants appears to be the largest current problem. However, the only objection to such growths is their contribution to the accumulating sediment. No attempt was made to remove the growths or to control their growth. At the end of eight years of operation they are still considered unobjectionable. Mosquito propagation has also been unimportant. Routine measures consist of occasionally oiling certain sections of the lake with the same frequency as unpolluted water and swamp areas in the vicinity.

The greatest long range problem of maintenance can probably be considered that of removal of sediment after it has accumulated to such an extent that the capacity of the reservoir is impaired. This would include removal of both silt and sludge residue. The total volume of residue, including silt, to be removed would be less at the end of eight years, in this instance, than the same volume of sludge to be handled from a digestion tank. Assuming a destruction of 50 per cent volatile matter in a digester, the equivalent volume of accumulated material to be disposed of from a digester at the end of eight years would be 77,000 cu. ft. with 90 per cent moisture content. This compares to an accumulation in the pond during a similar period, of 65,000 cu. ft. of sediment with 60 per cent moisture. The equivalent volumes with respect to air dried sludge would however be much smaller for the digester. On the basis of equivalent moisture contents the quantity of sludge would be about 22,000 cu. ft. from the artificial process as against 65,000 in the lake. It should be kept in mind that the greatest mass of deposit is caused by silt carried into the pond by the stream and from adjacent lands.

*Oxygen Demand of Sludge.*—Aside from immediate practical application in this situation, but of technical interest, is the indicated oxygen demand on the stream or reservoir water created by the sludge under natural stabilizing conditions.

Under operating conditions, where a continuous source of pollution exists, the composite unit oxygen demand of the sludge consists of rates created by material of composition varying from freshly deposited sludge to sludge which is the age of the sludge bank. Oxygen demand of the material is usually thought of in terms of freshly deposited material, with the presumption that after the customary carbonaceous

stages of decomposition observed in the laboratory, the demand of the sludge is essentially satisfied.

The foregoing data show a relatively rapid and extensive decomposition of freshly deposited sludge, but also a certain oxygen demand, either potential or active, which continues to exist after prolonged periods.

If the assumption is correct that the age of the deposit is proportional to the depth at which the sample is collected, this study indicates that even after an age of six years (lower deposit) the oxygen demand of the sludge deposits, as measured under laboratory conditions, may still persits at a rate which is of significant proportions.

The relative persistence of the oxygen demand of the organic material is shown further by comparisons with the results reported by Baity [1] and Rudolfs [3] which were obtained under aerobic conditions in the overlying liquor, similar to those existing under natural aerobic conditions.

| | Age of Material | Mg. B.O.D. per Gm. Vol. Matter (20 day) |
|---|---|---|
| Baity | Fresh material | 455 |
| This Study | Fresh (filter oxidized) | 540 |
| Rudolfs | 1 year old | 140 |
| This Study | 2 yrs. old (average) | 67.5 |
| This Study | 6 yrs. old (average) | 41.3 |

These figures show that while the rate of decomposition of the material decreases rapidly to a low figure after the first stages of decomposition, it still may persist on a volatile basis for a period of years. Although the volatile constituents as well as the B.O.D. decreases, it would seem possible that the cumulative effect of decomposition of this more resistant material may with the passage of time and quantitative accumulation amount to very significant figures as compared to the more freshly deposited material.

The extent of oxygen demand of the older material can be illustrated, on the basis of the previous data, with respect to the relative component demands of a unit volume of composite sludge bank 8 years old. This is shown by the following tabulation.

| Sludge Component | Relative Quantity of Sludge (dry) | Per Cent Vol. Matter | Mg. B.O.D. per Gm. Vol. Mat. Solids (20 day) | Total Oxygen Demand Mg. | Per Cent Demand Allocated to Each Sludge |
|---|---|---|---|---|---|
| Fresh material | 1 | 73 | 540 | 395 | 2.1 |
| 0 to 1 yr. old | 262 | 30 | 140 | 11,100 | 57.5 |
| 1 to 8 yr. old | 1,197 | 12 | 54 | 7,876 | 40.4 |

This tabulation indicates that whereas the oxygen demand of the oldest sludges per unit volume of material is only a small per cent of the demand of the fresh material, the relative total quantitative demand of

the old material in the sludge deposit amounts to significant proportions. The accumulated material from 1 to 8 years old appears to compose approximately 40 per cent of the total oxygen demand of the sludge deposit.

The important question in this consideration is whether the demand of this older material is potential or active. The active demand would depend on the contact between the sludge and overlying oxygen bearing medium by diffusion. Lack of diffusion and waste of by-products of decomposition in the older and lower strata of the sludge might also account for the slower rate of decomposition of the more resistant material. If such is the case the demand of the older material is largely potential and would exert small current effect on the depletion of the overlying waters. Increased effect would be exercised only by removal of the top strata of sludge or by thoroughly mixing with the overlying water.

On these premises a sludge bank can be considered as having two separate influences; first, an active demand for oxygen created by that material in contact, either physical or diffusory, with the oxygen bearing water, and second, a potential demand of significant magnitude created by the material decomposing under anaerobic conditions. The magnitude of each of these depends on the relative quantities operating under aerobic or anaerobic conditions. Likewise the current oxygen demand on the stream water will depend upon the quantitative relation between the aerobic and anaerobic portions of the deposit. The current oxygen demand upon the overlying water would be a minimum with a maximum proportion of the deposit under anaerobic conditions and conversely a maximum with the minimum proportion of the deposit under anaerobic conditions. The former would require that the sludge deposit be subjected to a minimum disturbance which is more easily obtained by impounded water than under stream conditions. Hence the impounded waters seem to give the additional advantage over normal stream disposal, of decomposing the suspended solids component of pollution with less oxygen demand on the stream waters.

*Nitrogen Changes in Sludge.*—The relative changes of carbonaceous and nitrogenous material during the course of decomposition in the reservoir are of interest. In the more artificial decomposition of organic material in sewage treatment plants, reduction of nitrogenous material lags behind carbonaceous decomposition and as a result constitutes a greater part of the oxygen demand during the latter stages of destruction. This tendency should be the same in the natural lake basin if the same fundamental factors of aerobic and anaerobic processes are active.

The results given in the following tabulation show the relation between nitrogen, B.O.D. and volatile matter in the sludges at various points in the lake.

It will be observed that in the earlier stages of decomposition the increment of decrease in B.O.D. exceeds the increment of decrease in nitrogen for the corresponding period, but in the later stages the in-

| | Ratio Mg. N per Gm. Vol. Matter | Per Cent Decrease | Increment of Decrease | Ratio Mg. B.O.D. per Gm. Vol. Mat. | Per Cent Decrease | Increment of Decrease |
|---|---|---|---|---|---|---|
| *Age Material* | | | | | | |
| Fresh | 83 | | | 540 | | |
| 2 yr. old | 29 | 64 | 64 | 67 | 87 | 87 |
| 6 yr. old | 25 | 70 | 6 | 41 | 92 | 5 |
| *Location of Material* | | | | | | |
| Fresh | 83 | | | 540 | | |
| At outfall | 41 | 50 | 50 | 118 | 78 | 78 |
| 100 ft. from outfall | 29 | 65 | 15 | 45 | 91 | 13 |
| 250 ft. from outfall | 27 | 68 | 3 | 22 | 96 | 5 |

crement of decrease is of the same order in both cases. This would indicate that the carbonaceous material is decomposed in the earlier period of destruction and the nitrogenous material constitutes the more resistant part of the later oxygen consuming stages. The data also shows, by the very small increments of decrease in the oldest material as corresponding to the relatively large percentage of nitrogen remaining, that the decomposition of the remaining nitrogenous material will be extended over a comparatively long period. This would appear to account in part for the persistent oxygen demand of the relatively old sludges in the deposit which was noted in previous parts of the discussion.

## Summary

Studies were made on the quantity, character and oxygen demand of sludge deposits formed in a lake receiving trickling filter effluent. Investigations included quantity of sludge accumulated, chemical composition with respect to solids, volatile matter, nitrogen, biochemical oxygen demand, and pH. Microscopic and bacterial examinations were made on the sludge.

The quantity of sediment accumulated amounted to approximately 23 cu. ft. of lake or reservoir capacity per ton of sewage solids per year which included sewage solids, natural silt accumulation and decaying vegetation. This amounted to a rate of accumulation of sediment of about 3 per cent per year of reservoir capacity.

Proportion of total sediment due to sewage solids only is estimated at 17 per cent of the total accumulation. This amounts to 3.9 cu. ft. of lake capacity per ton of sewage solids per year.

The character of the composite sludge deposit differed from non-sewage polluted sediment in the vicinity, principally with respect to biochemical oxygen demand, which though sufficiently low to prevent nuisances, was materially higher in the lake sludge-sediment. The volatile content of the sludge-sediment was also higher but the destruction of volatile matter amounted to 93 per cent within a relatively short

time. Other indices, such as pH, nitrogen and solids, were practically the same in the polluted and nonpolluted sludges.

The sediment showed a significantly higher degree of decomposition in the bottom layer than in the top layer. Horizontally, the sludge deposit was practically uniform with the exception of a small area surrounding the outfalls.

The studies on oxygen demand of the sludge by laboratory methods indicated a persistent demand by the older material, which although decreasing, constituted, due to mass accumulation, 40 per cent of the total composite demand of the entire sludge deposit. It is estimated that this demand was due largely to the more resistant nitrogenous plus remaining carbonaceous material and that the demand is potential rather than active.

Microscopic observations showed almost complete absence of protozoan forms in either the top or bottom strata of sediment. Bacterial counts were relatively low, amounting to approximately 310,000 to 380,000 per gram of material in the top and bottom stratas, respectively of the fresh material or 10,500,000 and 8,800,000 per gram of organic material. In the older sediment counts ran as low as 3,310,000 per gram of organic material. Fertile soils may have from 8,000,000 to 15,000,000 bacteria per gram of organic material.

The general results of eight years experience indicates that impounded bodies of water, operating under natural conditions, offer a capable unit in the process of sewage purification, where natural conditions are available for such purposes. This applies with respect to (1) reduction of B.O.D., suspended solids, and *B. coli* and (2) decomposition of settleable solids with less oxygen demand on the stream waters.

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# Industrial Wastes

## THE SEPARATION AND RECOVERY OF PAPER FIBRE FROM WASTE MILL WATER*

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This paper is intended to cover in a somewhat condensed form the methods used to separate and recover paper fibre from the waste mill water at the Number 3 Plant of the Consolidated Paper Company, Monroe, Michigan, together with some of the difficulties encountered and the results secured to date.

Since the author does not consider himself an authority on either the manufacture of paper board or on sewage disposal in general the paper is confined to a consideration of the methods employed and the results obtained in this plant.

All paper mills and particularly those that manufacture paper board use large quantities of water in the manufacturing process. The quantity varies with the kind and quality of board, the re-use of water and the control of water in the process. Information from a number of board mills indicates that the quantity of water used varies from 30,000 to 50,000 gallons per ton of product. In this plant the suspended solids content, as indicated by a number of sample tests, amounted to about 3.5 pounds per thousand gallons of water. In strawboard manufacture and in the manufacture of panel board in wet machine mills the solids content may be as high as 12 to 15 pounds per 1000 gallons, but the quantity of water used per ton of production is considerably less than in paperboard mills.

The principal product made at this plant is liner board. There are two board machines which have a combined output of 220 to 240 tons per 24 hours. The base or raw material used in the manufacture of the board is waste paper, of which there is normally an ample supply available at delivered prices from $6.00 to $8.00 per ton. Adjacent to the board mills are three straw mills which have a combined output of 110 tons per 24 hours and here also the raw product is very inexpensive and plentiful. The fact that the raw material is cheap has a most important bearing on the method of treatment.

The manufacturing process briefly is as follows: Mixed paper stock is broken up in beaters to the form of pulp. It is then thinned to a consistency of about 0.5 to 1.0 per cent solids by the addition of water, and pumped into settling troughs. From here it passes over an Oliver filter covered with a 40 to 60 mesh wire screen, on which the stock is dewatered. Two filters 8 ft. in diameter by 16 ft. long are used at

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this plant and each has a capacity of 125 tons of stock per day. The effluent from the filters contains from 1 to 1.25 pounds of fibre per thousand gallons of water.

Stock is then pumped to Jordans for further grinding, after which it is ready for formation in sheets. The machine used for producing the sheet consists of a series of six cylinders covered with screens, each revolving in a vat. The sheet is formed by picking thin layers of fibre off the screens by means of a felt, which then passes continuously over a system of dryers. Four of the cylinders are used for filler stock and two for liner. Each of the machines under discussion is equipped with five felt shower pipes, six cylinder showers, six foam showers and six screen showers. Each machine also has 96 dryers. Water for processing and washing is used in the beaker beaters, the finish beaters, for dilution of the beater stock, dilution at the head box and in all of the shower pipes.

For years fresh water had been used on all of the shower pipes and also on the Oliver filter showers before mentioned. Dirty water or white water from the machine chests has been used for beater water and for dilution in the settling trough.

All waste water flows to the rear of the mill, passes into a sewer and from there to an open ditch known as Mason Run. This ditch winds through a swampy area below the plant and eventually flows into River Raisin some two miles distant. Waste water from the straw mills and from the River Raisin Paper Company also flows into this channel. The combined daily total production of both plants is some 600 to 800 tons.

There is, of course, nothing new or novel in attempts to recover waste products in industrial plants. When the raw material is expensive or difficult to obtain the prevention of waste is naturally of importance, and considerable expense in recovery systems is justifiable. But when the raw material is plentiful and cheap, money spent in recovery equipment may prove to be a rather poor investment. Board mills in general fall into the latter classification. In this plant studies made over a period of years showed rather conclusively that the value of the recovered fibre would not justify any large investment in recovery equipment. Perhaps it is more correct to state that an equal amount of money invested in equipment to increase production would likely show a greater return than any attempt to salvage waste.

Appropriations made by the Federal Government a few years ago to dredge River Raisin and create a turning basin for commercial shipping made this river a government harbor subject to regulations imposed by the United States War Department. This Department is interested only in the prevention or the removal of deposits in the river or turning basin that would interfere with shipping and if these deposits are the result of manufacturing processes rather than natural causes the cost of dredging after the initial work was completed must be borne by the manufacturing interests. River Raisin is also subject to any restrictions and limitations that may be imposed by the Michigan

Stream Control Commission. The investigations made during the past three years are the result of an effort on the part of the manager, Mr. H. L. Rauch, to learn what changes in plant operation might have to be made to meet the probable requirements of these two government agencies, and to determine what methods of treatment might be adopted. The changes made are the result of some of these investigations.

In April, 1936, engineers from the Dorr Company were retained to make a plant survey and to recommend a method and the necessary equipment for separating the solids from the waste water. Working with the plant engineers, they submitted a rather complete report on the subject. Their final recommendation was to construct a large sedimentation tank in the swamp about a mile below the plant. Here the separated solids could easily be disposed of by being used for fill or by burning. The clear effluent would flow into the River Raisin. There is no doubt in the mind of the writer that this plan would produce rather effective results although some difficulty might be met in straw mill wastes. It would, however, involve an enormous investment and the separated solids, which are mostly prepared paper stock, would be thrown away.

As previously mentioned, separation of paper stock from waste water can be accomplished to a certain degree by filtering or by mechanical screening and the stock thus recovered may be returned directly to the system. At this stage of the process the stock fibre is considered to be worth $10 to $12 per ton. It was decided, therefore, to experiment with save-all equipment of the mechanical screen type. If later it became necessary to improve the clarification by sedimentation, the investment in tanks and equipment would be much smaller than if the entire separation were made by sedimentation. In this type of save-all equipment a cylindrical drum about 10 ft. in length and 42 in. in diameter, covered with screen cloth, revolves slowly in a vat. As white water flows into the vat and through the screen the paper fibre is collected on the outside of the screen covering. As the drum revolves this stock is couched off by contact with a rubber roll and returned to a stock chest while the water flows into a sump from which part of it can be recirculated in the process and the rest diverted to the sewer.

Since the recovered fibre is usually more finely divided and shorter than the average fibre going into the board, there is a question of whether the return of this fibre to the stock chest will weaken the finished sheet. However, the percentage of recovered fibre is relatively small and no difficulty has been experienced.

The effectiveness of mechanical screening depends upon the fineness of mesh in the cloth used and also upon the per cent of fibre in the waste water. If the mesh is too fine the flow is slow and large machines are required. In general, the heavier the fibre the more effective the separation. Therefore a reduction in quatity of water will immediately improve mechanical separation However, any attempt to reduce the quantity of water on a paper machine is likely to bring considerable

opposition from the machine room superintendent. So far as the writer has observed, few machine operators are ever provided with a sufficient quantity of water at a high enough pressure and it is undoubtedly true that an excess of water makes operation somewhat easier.

It seemed apparent that the recirculation of water through at least a part of the showers would be a start in the right direction. Fortunately the superintendent was willing to cooperate but it was first necessary to prove conclusively whether or not the recirculated water would plug the shower pipes or cause other operating difficulties. So a small pump was installed to pump white water through two cylinder showers. No serious trouble was experienced.

Two mechanical revolving screens or save-alls were first installed near one machine. All the water leaving the machine was passed through these save-alls, and the separated fibre was pumped back to the stock chest. The effluent flowed to a sump from which part of the water was recirculated through the screen, cylinder, and foam showers. The surplus water was discharged to the rear of the plant and used as previously indicated. Fresh water was used on the felt showers. Later, two additional save-alls were installed for the second machine and similar arrangements were made to recirculate water on this machine.

In a further effort to reduce the total quantity of water entering the plant, quantity tests were made on individual shower pipes. Shower pipes have 50 to 60 orifice openings, each 3/16 in. in diameter. In some cases the openings had become so enlarged by wear that they were passing approximately double the original quantity of water. These pipes were replaced as rapidly as possible. An excessive quantity of water is, of course, no disadvantage in the manufacturing process unless it is accompanied by a drop in pressure. High jet pressure rather than large quantity appears to be most effective in keeping the felts clean.

Recirculation of white water and reconditioning the shower pipes resulted in a reduction of about 40 per cent of fresh water entering the mill and no trouble has been experienced in production or in the quality of the board. This reduction in water consumption and the partial separation of solids reduced the solids in the effluent to about 1.25 pounds per thousand gallons of water. Combining the reduction in quantity of water with the reduction in per cent of solids has resulted in a total reduction of nearly 60 per cent of settleable solids since the plant changes were made. The actual reduction in water amounts to about 2500 gallons per minute and the recovered paper fibre from 5 to 7 tons per day. Results to date would seem to indicate that the value of the recovered stock would amount to $50 to $70 per day if we assign a cost of $10 to $12 per ton at this stage of the processing. The pumpage costs have also been materially reduced. To partially offset this gain, four save-alls have been installed at a total cost of about $20,000. Each save-all is equipped with a one horsepower motor.

A complete clean-up of each screen must be made once a week. Additional chlorination is required because of the recirculated dirty water. The cost of maintenance is unknown to date but will not likely be high. It is quite probable that the installation will prove to be a fair investment.

An examination of the above figures would indicate that a greater percentage of reduction had been made but the waste water from the straw mill is also diverted into the same sewer with the water leaving the board machines and the straw mill waste carries a considerably higher solids content.

As an additional experiment a save-all machine with a 70-mesh wire cloth was installed in the straw mill but the results were not satisfactory. This result is supported by a statement contained in the report by the engineers of the Dorr Company, "There is no known method by which stock and waste water from straw mills can be recovered."

The experiment referred to in Mr. Kronbach's paper *q.v.* was made in the Number 1 plant. This is a wet machine mill manufacturing a heavy board heavily impregnated with asphalt. Neither the manufacturers of the save-all equipment nor the plant engineers had much confidence in this experiment as it was thought that the asphalt content of the waste water would rapidly fill the save-all screen, which would require constant cleaning. Much to everyone's surprise no difficulty was experienced and while no accurate data are available on the amount and value of the recovered solids it is apparent to all that this has proved to be an excellent investment from the standpoint of the Consolidated Paper Company.

Experimental work has also been carried on in the South Side Plant but here the problem is complicated by the fact that a rather wide variety of board is produced, much of which contains coloring in some form. Separated paper stock cannot be stored in chests for any length of time but must be returned to the system as soon as possible. When an order is completed and the machine is being prepared for a change of board, any stock on hand must be discharged to the sewer or formed into heavy sheets and dried. Attempts to recirculate water which contains coloring must, of course, be approached very cautiously. In pulp mills the use of save-alls is common and a wet machine may be used in conjunction with the save-all to convert the separated stock into kraft, which can be stored and used at a future time or sold to other mills.

It is probable that the most successful separation of stock from waste water in the South Side mill of the Consolidated Paper Company will be by the sedimentation process. Whether the separated stock can be economically returned to the system is still a question. It is proposed to continue this work during the present summer.

We must not conclude, however, that plain sedimentation will produce a 100 per cent clear effluent. Laboratory tests indicate that in this plant approximately 95 per cent of the settleable solids will precipitate in 2½ hours, while less than half of the suspended solids will be

removed. Furthermore only 64 per cent of the suspended solids were removed in a 24 hour detention period.

This would seem to prove rather conclusively that complete separation can be accomplished only by the addition of some settling agent such as lime or alum. But the use of settling agents is likely to contaminate both water and stock so as to render it unfit for further use in the plant.

From the results of these experiments we can safely deduce the following:

*First,* the conditions in each plant or mill must be carefully analyzed and the treatment method adopted that will best suit these conditions. No two plants are alike.

*Second,* mechanical screening may prove to be profitable to the company up to a certain point of recovery.

*Third,* the practical limit of mechanical recovery seems to be between 1.00 and 1.25 pounds per thousand gallons of water.

*Fourth,* separation of straw mill waste is extremely difficult, if not impossible by this method, unless the waste water is mixed with that of the board mill.

*Fifth,* closer supervision and control of the plant equipment will result in an appreciable reduction in water pumpage without affecting the operation.

In conclusion the author wishes to acknowledge his indebtedness to the Dorr Company, to Mr. J. C. Ainslie, Engineer, and Mr. Oliver Roverts, Chemist of the Consolidated Paper Company, and to the engineers of the Michigan Stream Control Commission, all of whom have played an important part in this co-operative effort to secure information which may assist not only the paper industries of the State but also lead to the clearing up of our Michigan streams.

# HANDLING PAPERMILL WASTE IN THE MONROE SEWAGE TREATMENT PLANT*

By Allen J. Kronbach

*Superintendent, Monroe Sewage Treatment Plant*

The general plan for collecting sewage from the City of Monroe is with large interceptors on each side of the river, using the south interceptor as the main sewer and connecting the north side sections with it through river crossings in the river dams. The sewer system of Monroe is not altogether a separate system as there are several combined drains connected into it but these are being taken out as soon as possible.

The sewage of the City of Monroe, composed of domestic and industrial wastes, flows by gravity to the sewage treatment plant. The largest industrial wastes are papermill wastes of the Consolidated No. 1 Plant and the Monroe Paper Products Co., which together contribute about two-thirds of the sewage treated.

The Monroe Plant is a primary treatment plant with separate sludge digestion. When the sewage reaches the plant it passes through a comminutor or, in case of high flows, through a bar screen to the pump well. Raw sewage pumps lift the sewage 15 feet. It then flows through the detritor or grit removal machinery, raw sewage meter and clarifiers. The settled sewage flows back into the building where in warm weather it is chlorinated and passes through a contact chamber before it reaches the river. The sludge is digested in a Dorr Multi-digestion system, which has floating covers for gas collection and storage. The gas formed is used for heating the digestor and building and for operating a gas-engine driven sewage pump. The digested sludge is dried on open drying beds and has been used mostly for fill as its fertilizer value is very doubtful because of the amount of paper pulp in it.

There are two types of paper machines in the papermills discharging into our plant, each of which make paper from wood, rags and waste paper. They are the wet machines and multi-cylinder machines. The waste from these machines, called the white water, is quite large in volume and contains considerable amounts of fiber, filler, alum and dirt. Fiber is the most important of these constituents.

The white water greatly assists sedimentation because it acts as a coagulant. The floc formed settles quickly and brings a major portion of the suspended matter down with it.

The color of the final effluent is affected by the type of paper that is being manufactured. One of the plants makes a black panel board for automobiles and although the effluent may be very low in suspended solids it colors almost half of the river black.

* Presented at the Fourteenth Annual Conference of the Michigan Sewage Works Association, East Lansing, March 30, 1939.

The sludge formed from this mill waste concentrates very quickly and when its concentration gets above 5 per cent solids it is almost impossible to remove it from the clarifiers without dilution. The appearance of the sludge is very deceiving. It may appear to contain 7 or 8 per cent solids when it is actually only 4 per cent. It was found that the best way to handle this sludge is to pump it almost continuously and not let a sludge blanket form in the clarifiers. It is removed at a solid content of between 3 and 4 per cent solids.

Frequently the mills will dump an experimental beater of paper pulp which causes our clarifiers to plug and then it is a slow process to remove the sludge because the scrapers can only be moved a little at a time in order that too much sludge may not get into the sludge hopper at one time.

One of the Monroe mills whose waste is treated at the plant has a large breaker beater into which whole unsorted bales of paper are dumped. This beater is cleaned once a week and all sorts of material such as blocks of wood, sticks, electric light bulbs and old bags flow into the treatment plant. The sticks and blocks of wood cause the most trouble because they break the cutters of the comminutor and go through the screen, become water soaked and settle in the clarifiers. When the blocks are pumped with the sludge they cause the ball checks of the sludge pumps to be held open, necessitating frequent cleaning of the pumps. As much of the wood as possible is skimmed from the raw sewage at the comminutor and a screen has been installed at the paper mill but still the blocks get through.

In the manufacture of asbestos paper there is quite a bit of foaming which causes additional loss of fiber. This condition is easily noticeable in the plant influent because it turns gray and looks like a thick soup. Asbestos fiber settles quickly and this means that sludge must be pumped continually.

Papermill waste sludge forms scales of paper wherever it dries. It is easily removable, however, as it can be peeled off with a knife. If a thin layer of sludge is placed on the drying beds it can be taken off in large sheets. With the sand of the bed sticking to it, it has the appearance of tar roofing paper. On thick applications the fibers seem to flatten out and form into layers.

Since the treatment plant was started, an average of 57,000 gallons of sludge has been pumped from the clarifiers daily. The two digestors have a capacity of about 1,000,000 gallons so that there is a complete turnover of sludge in about twenty days. In the spring as soon as weather permits digested sludge is placed on the drying beds. It is removed as soon as it is dry enough to handle and the beds are constantly in use until late in the fall.

The large amount of sludge, due to the amount of solids in the sewage and the inability to remove a concentrated sludge from the clarifiers, affects gas production in cold weather. So much sludge is pumped that the digestors cannot be heated properly, which results in lower gas production. The gas production fell from an average of

20,098 cu. ft. in August to 2,095 cu. ft. in February. This winter, pumping part of the raw sludge directly to a lagoon was tried, but this did not help, probably because there wasn't much digestible material getting into the digestors.

In the digestor the sludge forms into three layers, heavy fibrous-like material at the top, a thinner supernatant liquor in the center, and a heavy sludge at the bottom. It is doubtful if the turbo-mixer in the primary tank does very much good because it doesn't seem to disturb the sludge a foot from the end of the paddles. This is especially true of the top layer.

When the plant had been in operation for about six months it was noticed that heating water was being lost in the system that heated the digestor, and rubber bands along with paper fiber were found in the circulating pump of the system. This led to the conclusion that there must be a leak somewhere in the digestor heating coils. After the digestor was emptied of sludge the coils were found to be broken in several places and lay in a twisted mess on the bottom. The coils were repaired and fastened with U-bolts to the pegs on which they had formerly just been supported and four joints were welded. It is hard to explain this break but the raising and lowering of the sludge level may have lifted the coils from the supporting pegs and broken some of the connecting fittings. This seems quite plausible because a man could have walked all over the top of the sludge in the digestor with the help of a plank.

In the secondary digestor the supernatant line was set two feet from the top surface of the sludge. This line never could be kept open. For a time the emergency overflow line was used as a supernatant line but this was unsatisfactory. A line that could have been used as a discharge line into the secondary digestor was used to take off a supernatant. This line gave a good supernatant liquor but it could only be used between raw sludge pumping periods. By sampling the digestor it was found that a supernatant existed about six feet below the surface of the sludge. Five feet was cut from the top of the supernatant pipe and three one-inch bars were welded to it as guides so that, if conditions change and the pipe would need to be raised, it could be done by opening the manhole directly over it and slipping short pieces of pipe over the bars. The supernatant line works very satisfactorily now.

The digested sludge meter, used to measure sludge discharged to the drying beds, had only a 1½ in. throat and was always plugged with rags or sticks. This meter was removed and replaced with a piece of 6-in. pipe. The digested sludge is now measured by the depth placed on the beds.

In the very near future a large share of the paper waste is to be removed, as the Monroe Paper Products Company have now under construction two clarifiers and floculators for the treatment of their waste. Another plant has also placed one save-all in operation and are planning to clean up their waste even more.

There are several advantages that the Monroe Paper Products

Company hope to gain from the installation of their own plant: (1) they will recover about four tons of paper stock daily that has already been processed; (2) they will be able to reuse the water at a great saving in heating; (3) they will save in chemicals; and (4) they will eliminate the payment of a city sewage charge.

If these mills had not started to clean up their own waste it would be necessary for the Monroe Sewage Treatment Plant to find some means of disposing of sludge such as vacuum filters or ponds but this does not seem likely at the present time.

The following results are plant averages since the plant has been in operation.

| | |
|---|---|
| Flow | 5.6 M.G.D. |
| Grit Removal | 12.4 cu. ft. per day |
| B.O.D. Influent | 124 p.p.m. |
| B.O.D. Effluent | 72 p.p.m. |
| B.O.D. Reduction | 41.9 per cent |
| Settleable Solids, Influent | 19.2 ml. |
| Settleable Solids, Effluent | 0.8 ml. |
| Settleable Solids, Removal | 95.8 per cent |
| Total Solids, Influent | 928 p.p.m. |
| Total Solids, Effluent | 694 p.p.m. |
| Total Solids, Removal | 25.3 per cent |
| Suspended Solids, Influent | 327 p.p.m. |
| Suspended Solids, Effluent | 84 p.p.m. |
| Suspended Solids, Removal | 74.3 per cent |
| pH, Influent | 7.2 |
| pH, Effluent | 7.2 |
| Raw Sludge Removal | 57,042 gallons per day |
| Moisture Content | 96.6 per cent |
| Volatile Content, Dry Basis | 72.6 per cent |
| Gas Production | 10,598 cu. ft. per day |

# Operators' Reports and Suggestions

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## THREE YEARS EXPERIENCE WITH RATING SEWAGE TREATMENT WORKS OPERATORS' ANNUAL REPORTS

By Stanley T. Barker

*Chairman, Rating Committee, New York State Sewage Works Association*

In 1936 the Rating Committee of the New York State Sewage Works Association rated the first set of annual reports from sewage treatment works operators in New York State who had prepared their reports to cover all the items called for in the Rating Schedule of the Association which was published in the March, 1935, issue of This Journal. These reports were submitted in the competition for the Association's award for the report which most nearly furnished all the operating and control data required by the Rating Schedule for the treatment units contained in their respective plants; and in 1937 and 1938 similar competitions were held and awards made.

During these three competitions the Rating Committee, whose membership during this period has included A. F. Dappert, Wellington Donaldson, John R. Downes and Stanley T. Barker, has reviewed the various reports with great interest, and it has been a matter for congratulation that the Committee has never had any difficulty in agreeing on the report to be given the award for that year. In each competition there has been one report which had a rating several per cent higher than any of the others, but if there had been awards for second and third choice it might have been quite difficult to reconcile the individual ratings by the three members of the Committee so as to determine who would have been entitled to second and third places in the competition.

In each of the three competitions there have been about eight contestants, but to those who know the desirability of the award it seems very surprising that there have not been more. Also, as has been pointed out a number of times, there is a real advantage to an operator who enters the competition even if he does not win the award since he obtains, through the compilation of his report, a better understanding of the operation of his plant and his superiors are notified of, and congratulated on, the enterprise and interest shown by their plant operator.

The winning percentages in these competitions has been as high as 95 per cent, while reports have been received which rated as low as 46 per cent. These low ratings were in most part caused by the failure

of the operator to furnish all the information required by the schedule, so the Committee wishes to urge that all contestants in such a competition make very certain that they give an appropriate answer for every item in the schedule which applies to their plant.

In fairness to the other contestants the Committee must mark the reports in strict accordance with the schedule, so any omitted item means a definite loss of possible credits.

The winner in 1936 was C. George Andersen of Rockville Center, and it is felt that readers of THIS JOURNAL will remember seeing Mr. Andersen's name mentioned many times since he received the first award. In 1938, he was elected to the Executive Committee of the New York State Sewage Works Association and at the January meeting in 1939 he was elected Vice-President of the Association.

H. O. Johnson of the Belgrave Sewer District was the winner of the second award and Elvey A. Marshall of Geneva won the award in 1939, and all three of these former winners continue to send in copies of their annual reports to the Rating Committee, even though they are no longer eligible to compete for the award.

The three winning operators are from plants having nominal rated capacities of 1.0, 2.0 and 3.4 m.g.d. respectively, so any operator from any size of plant should feel himself competent to turn in a winning report, if he has the equipment necessary to permit him to make the simple control tests that are required by the schedule.

It should be pointed out that the Rating Schedule was set up and approved by men who are thoroughly conversant with plant operation, so no test results are called for by the schedule unless these tests are needed for the proper control of and the proper operation of the plant. Under such circumstances, any operator who lacks equipment to make the tests which are called for by the Rating Schedule, should feel justified in asking that he be supplied with the necessary equipment, not only so that he may make a complete report, but, more especially, so that he can operate his plant properly.

The following article discusses the revisions in the original Rating Schedule which have been found desirable, and the Rating Committee feel that this revised schedule will be more workable than the one used thus far. From the experience obtained in three competitions, it is felt that these competitions are well worth while and that other member groups of the Federation would do well to sponsor similar competitions.

The operators who have taken part in these competitions have all expressed themselves as feeling repaid for the time and work they have spent and many of them have obtained a recognition of their efforts that would never have been realized if they had not entered reports in these competitions.

# REVISION OF RATING SCHEDULE FOR RATING ANNUAL REPORTS BY OPERATORS OF THE NEW YORK STATE SEWAGE WORKS ASSOCIATION

By Wellington Donaldson, A. F. Dappert, and Stanley T. Barker,
*Chairman, Rating Committee*

After an experience of four years with the Rating Schedule adopted by the New York State Sewage Works Association in 1935, certain minor deficiencies in the schedule have been recognized by the Rating Committee. Therefore, after considerable discussion by the present members of the Committee, and with the approval of the Executive Board of the Association in October 1938, the following schedule was drawn up and will go into effect when the reports covering the year 1939 are being written and rated. Because of the fact that this revised schedule is being printed in the May, 1939, *Sewage Works Journal* and may require additional records beyond those kept by the operators during the early portion of 1939, allowance will be made for this in rating the reports for 1939; and New York State operators will be required to report on the basis of the new schedule only for that portion of the year subsequent to May, 1939. Reports will be required covering the whole year, but those for the early months may be made on the basis of the old schedule and need not be as complete as those for the months beginning June, 1939.

At this time it seems proper to reprint at least a portion of the report of the original Rating Committee which sets forth the objects of the Association, but the wording of certain paragraphs will be changed to express the present spirit of the plan.

## Plans for Rating of Sewage Treatment Works Operators Reports According to the Adequacy of Operating Data and Records

### *General*

1. A standing committee to be known as the Rating Committee shall be appointed by the New York State Sewage Works Association to act as the reviewing authority on reports submitted to it.

2. The Rating Committee shall endeavor to enlist the cooperation of operators and to secure the submission of reports conforming in general to the outline contained in the schedule attached hereto.

3. The general basis for the award by the Rating Committee to plant operators shall be an annual report furnishing pertinent information concerning the plant and summary data for each month of plant operation.

4. As a stimulus for the submission of such reports, the N. Y. S. S. W. A. shall make available to the operator whose report receives the highest rating, a N. Y. S. S. W. A. award known familiarly as " The

Rating Award," provided, however, that no operator who has previously received this honor shall be eligible to receive a second award. As a further stimulus for the submission of such reports, the Rating Committee shall write a special complimentary letter to the municipal officials commending each operator who submits a report for his participation in this enterprise.

It is greatly desired that previous winners shall continue to submit their annual reports to the Committee even though they may not be eligible to receive the award, so similar complimentary letters shall be written to the appropriate municipal officials to acknowledge the co-operation of these previous winners in the work of the Association.

5. In the interest of disseminating information the Rating Committee should arrange for publication of the reports submitted, if feasible. If many reports are submitted the Committee should prepare a summary and have this published. Publication of reports or data submitted to the Rating Committee will be conditioned on consent of local authorities.

6. Ratings of the reports submitted shall be in accordance with the schedule of credits assigned in the attached outline which is based upon the recommendations made by the Committee on Sewage Works Operating and Cost Records of the Federation of Sewage Works Associations as published in the January, 1932, issue of THIS JOURNAL.

7. In determining the final rating for each report the ratings for Schedules I, II, III, and IV shall be calculated separately, these ratings to comprise the ratio of the total credits assigned by the committee to the total possible credits that would be assigned for a perfect score for whatever treatment processes are employed at the particular plant, thus resolving the separate ratings for each schedule to a percentage basis. The final rating shall be calculated as follows:

To the rating for Schedule I, add six times the rating for schedule II, one times the rating for schedule III, and two times the rating for schedule IV, and divide by 10.

8. The Committee is aware that in attempting to devise a rating system applicable to all types of sewage treatment, deficiences of the proposed system will develop which call for modification from time to time. No change in the numerical rating, however, shall be made without the approval of the Executive Committee of the N. Y. S. S. W. A.

It is the intent of this plan that these annual reports shall be rated in such a manner that a complete report from a small simple plant which gives the required data on the items appropriate to that plant shall receive as high a mark as a complete report from a large complicated plant. In other words, the operator of a small plant has an equal opportunity with the operator of a large plant, and each need only follow implicitly the schedules applying to his plant in order to obtain a perfect mark.

*Explanatory*

The following condensed summary of the items and credits given in Schedules I, II, III, and IV of the Rating Schedule and the explanatory remarks which follow will facilitate an understanding of the general principles of the proposed rating system without detailed study of the schedules themselves.

CONDENSED SUMMARY OF RATING SCHEDULES

| | No. Items | Credits |
|---|---|---|
| Schedule I. Descriptive and General Information | 18 | 100 |
| Schedule II. Operating Data and Practical Control Tests | | |
| A. Grit Chambers | 5 | 50 |
| B. Grease Removal (Separate Process) | 5 | 50 |
| C. Coarse Screens | 5 | 50 |
| D. Screenings Grinders | 4 | 50 |
| E. Fine Screens | 6 | 100 |
| F. Septic Tanks | 8 | 100 |
| $G_1$. Primary Sedimentation, Plain Tanks | 8 | 100 |
| $G_2$. Primary Sedimentation, Mechanical Tanks | 10 | 100 |
| $G_3$. Imhoff Tanks | 14 | 100 |
| H. Chemical Precipitation | 8 | 100 |
| I. Dosing Devices | 6 | 50 |
| $J_1$. Trickling Filters | 8 | 100 |
| $J_2$. Contact Beds | 8 | 100 |
| $K_1$. Secondary Sedimentation, Plain Tanks | 7 | 100 |
| $K_2$. Secondary Sedimentation, Mechanical Tanks | 9 | 100 |
| $K_3$. Secondary Clarifiers (Act. Sludge Plants) | 8 | 100 |
| L. Intermittent Sand Filters | 10 | 100 |
| M. Chlorination | 7 | 100 |
| N. Aeration Tanks (Activated Sludge) | 13 | 100 |
| O. Sludge Concentration Devices | 3 | 50 |
| P. Sludge Digestion Tanks | 13 | 100 |
| Q. Sludge Drying Beds | 9 | 100 |
| R. Sludge Analyses (unless included in III-G) | 8 | 100 |
| S. Vacuum Filters for Sludge Dewatering (Centrifuge) | 15 | 100 |
| T. Vacuum Filters Treating Sewage or Effluent | 12 | 100 |
| U. Other Filtration Devices | 5 | 100 |
| V. Incineration (or Drying by Heat) | 12 | 100 |
| W. Gas Collection | 4 | 50 |
| X. Gas Utilization | 4 | 50 |
| Schedule III. Analyses | | |
| A. Raw or Bar-Screened Sewage | 3 | 50 |
| B. Fine Screen Effluent | 2 | 100 |
| C. Settled Effluent | 3 | 100 |
| D. Filtered Effluent | 5 | 100 |
| E. Final Effluent | 6 | 100 |
| F. Stream Above and Below Plant | 5 | 100 |
| G. Sludge Analyses | 11 | 100 |
| Schedule IV. Cost Data | | |
| A. Original Plant and Additions | 3 | 50 |
| B. Maintenance and Operation | 13 | 100 |

Since the items applicable to each plant are scored on a percentage basis, the perfect score would be:

| | | |
|---|---|---|
| Schedule I | $100 \times 1 =$ | 100 |
| Schedule II | $100 \times 6 =$ | 600 |
| Schedule III | $100 \times 1 =$ | 100 |
| Schedule IV | $100 \times 2 =$ | 200 |
| Total | | 1000 |
| Rating 1/10 of total | = | 100 |

The following example will indicate how the rating system would be applied to a report covering operation of a plant consisting of a bar screen, primary sedimentation tanks with mechanical sludge removal, sludge digestion tank, gas collection, chlorination, and glass-covered sludge drying beds. The report would in general be expected to follow the outline as given in the Rating Schedule, the data and information being supplied under appropriate headings to enable rapid checking against the items for which credits are given. Where all of the information asked for under each item is given, full credit would be allowed. In case of incomplete or partial answers, credits would be allowed in proportion to the completeness of the data furnished.

However, at the meeting of the executive board in October 1938, the Rating Committee was authorized to use their judgment in assigning credits in cases where a report may give complete answers to the item in the schedule but where the number of tests made are insufficient for proper control of the portion of the process being reported on. That is, if one operator reports making daily tests while another has made only two or three tests a month, and the committee feels that daily tests are really necessary for proper control of the process, the committee may assign a higher credit for this item to the man making the more complete tests. If, however, infrequent tests are thought to be sufficient, the report with the more frequent tests would receive no higher credit than the other.

Assume that in Schedule I complete data are furnished for all items except items 15, 16 and 17 (which relate to average, maximum, and minimum estimated or measured daily sewage flows). The total allowable credits for these three items are 14 out of a possible 100, so under this assumption, the rating for Schedule I would be 86 per cent.

Items 1 and 2 of Schedule I will indicate the sections of Schedule II which are to be used. In this example the report would be expected to include data and information for the following:

II–C. Coarse Screens (5 items with possible credits totaling 50)
$G_2$. Primary Sedimentation (Tanks with Mechanical Equipment) (10 items with possible credits totaling 100)
M. Chlorination (7 items with possible credits totaling 100)
P. Sludge Digestion Tanks (13 items with possible credits totaling 100)
Q. Sludge Drying Beds (9 items with possible credits totaling 100)
R. Sludge Analyses (8 items with possible credits totaling 100)
W. Gas Collection (4 items with possible credits totaling 50)
X. Gas Utilization (4 items with possible credits totaling 50)

Assume that for Schedule II the report supplies full information and data except for Section R and item 3 of Section W (Average $CO_2$ content of gas each month). The total possible credits for Sections II–C, $G_2$, M, P, Q, R, W, and X above are 650. Under the foregoing assumption the total credits that would be allowed are 540. The rating for Schedule II would, therefore, be calculated as 540/650 or 83.1 per cent.

Assume now that the plant serves a population of 5,000 and has laboratory equipment for determination of B.O.D. but no equipment for suspended solids tests. For Schedule III data would then be expected to be submitted on the following sections:

III–A. Raw or Bar Screened Sewage Analyses
- Item 1. General method sampling, etc. (total possible credits = 10)
- Item 2. B.O.D. data (total possible credits = 20)
- Item 3. Suspended solids (no data would be expected)

C. Primary Tank Effluent Analyses
- Item 1. General method of sampling (total possible credits = 16)
- Item 2. B.O.D. data (total possible credits = 42)
- Item 3. Suspended solids (no data would be expected)

F. Analyses—Stream above and below plant outlet
- Item 1. General method of sampling (total possible credits = 20)
- Item 2. Estimate of stream flow (total possible credits = 20)
- Item 3. B.O.D. data (total possible credits = 20)
- Item 4. D.O. data (total possible credits = 20)
- Item 5. Relative stability data (total possible credits = 20)

Assume that complete data are furnished for all sections in Schedule III except items 4 and 5 of Section F. The total possible credits for Schedule III would be 188 and the credits that would be allowed under the above assumptions would be 148. The rating for Schedule III would, therefore, be calculated as 148/188 or 78.5 per cent.

Assume that for Schedule IV on Cost Data, complete data are furnished on all items in Sections A and B. The rating for Schedule IV would, therefore, be 150/150—100 per cent.

Recapitulating, the ratings for each schedule and the final rating would be as follows:

| | Rating | | Weight | | Total |
|---|---|---|---|---|---|
| Schedule I | 86 | × | 1 | = | 86.0 |
| Schedule II | 83.1 | × | 6 | = | 498.6 |
| Schedule III | 78.5 | × | 1 | = | 78.5 |
| Schedule IV | 100 | × | 2 | = | 200 |
| | | | | | 863.1 |

$$\text{Final Rating} = \frac{863.1}{10} = 86.31 \text{ per cent.}$$

# RATING SCHEDULE

## OUTLINE FORM OF REPORTS TO BE SUBMITTED TO RATING COMMITTEE AND CREDITS TO BE ASSIGNED IN THE CALCULATION OF FINAL RATINGS

### SCHEDULE I

*Descriptive and General Information*

(Required in all reports regardless of type or size of plant)

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. List of all treatment processes in sequence of sewage flow, such as bar screens, screenings, grinders, grit chambers, sedimentation tanks, trickling filters, final settling tanks and chlorination, etc. | 10 |
| 2. List of all sludge treatment and accessory processes, such as sludge digestion tanks, sludge drying beds, incinerators, vacuum filters, etc. | 10 |
| 3. Is flow entirely by gravity through plant to stream or is sewage or effluent pumped? Explain. | 4 |
| 4. Date plant was placed in operation | 4 |
| 5. Design basis of original portion of present sewage works as to volume of sewage to be treated and population to be served. | 8 |
| 6. Date and nature of subsequent additions | 4 |
| 7. Present population served by sewage works and how obtained | 8 |
| 8. Separate or combined sewers and percentage of each | 5 |
| 9. Give number of storm water diversion outlets or bypasses and the number of days each month such devices are in operation | 4 |
| 10. State nature and importance of industrial wastes tributary to sewage works; give strength and quantity, if possible | 5 |
| 11. Method of measuring or estimating sewage flow | 5 |
| 12. General purpose of sewage treatment such as protection of down-stream water supply, prevent nuisance conditions in stream, etc. | 4 |
| 13. Are separate meters available at plant for proportioning power consumed by various processes? | 5 |
| 14. Give total electric power used each month in K.W.H. and power used separately by each unit in treatment process for which a separate meter is available | 6 |
| 15. Average daily sewage flow entering plant for each month } Present 15, 16 and 17 in tabular form { | 6 |
| 16. Maximum daily sewage flow entering plant in each month } Present 15, 16 and 17 in tabular form { | 4 |
| 17. Minimum daily sewage flow entering plant in each month } Present 15, 16 and 17 in tabular form { | 4 |
| 18. List of employees at plant and approximate time spent by each in operating or maintaining plant | 4 |
| Total credits in Schedule for perfect score | 100 |

### SCHEDULE II

*Operating Data and Practical Control Tests*

(Rating shall be applied to all of those sections indicated in items 1 and 2 in Schedule I plus any others that should be included. Omit rating on the sections below which do not apply.)

#### A. GRIT CHAMBERS.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of grit chamber or detritor and number of units; give average velocity and detention period, based on present average flow | 10 |
| 2. Frequency of grit removal or grit chamber cleaning | 8 |

| *Item Reported Upon* | *Credits* |
|---|---|
| 3. Cubic feet of grit removed each month and cu. ft. per m.g. | 16 |
| 4. Method of handling and disposing grit | 8 |
| 5. Give h.p. of motors and average hours used each day | 8 |
| Total credits for perfect score | 50 |

## B. Grease Removal (if separate from and in addition to items F, $G_1$, $G_2$ and $G_3$ of this schedule).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of device. Describe essential features | 8 |
| 2. Give data on air and chemicals used per gallon or per million gallons of sewage | 12 |
| 3. Frequency of grease removal | 8 |
| 4. Cubic feet of grease removed each month and cu. ft. per m.g. | 16 |
| 5. Method of handling and disposal of grease | 6 |
| Total credits for perfect score | 50 |

## C. Coarse Screens (hand raked or mechanically cleaned).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of screen, number of units and clear openings between bars | 8 |
| 2. Frequency of screenings removal | 8 |
| 3. Cubic feet of screenings removed each month and cubic feet per m.g. | 16 |
| 4. Method of handling and disposal of screenings | 8 |
| 5. Give h.p. of motors and average hours in use each day | 10 |
| Total credits for perfect score | 50 |

## D. Screenings Grinders.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type, rated capacity and number of units | 12 |
| 2. Average hours attendance required per day | 14 |
| 3. Describe frequency and seriousness of repairs | 12 |
| 4. H.p. of motors and average hours in use each day | 12 |
| Total credits for perfect score | 50 |

## E. Fine Screens.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of screen, rated capacity, number of units and clear openings | 20 |
| 2. Filtering medium added in cu. ft. per m.g.—give for each month | 20 |
| 3. Cubic feet of screenings removed each month and cu. ft. per m.g. (where a filtering medium is added, give total quantity of material removed from screens) | 25 |
| 4. Method of handling and disposal of screenings | 15 |
| 5. Average dry solids content of screenings removed each month | 10 |
| 6. Give h.p. of motors and average hours in use each day | 10 |
| Total credits for perfect score | 100 |

## F. Septic Tanks.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of tanks, total capacity and number of units | 10 |
| 2. Detention period based on present average sewage flow | 8 |

| *Item Reported Upon* | *Credits* |
|---|---|
| 3. Frequency of sludge removal | 7 |
| 4. Cubic feet of sludge and scum removed each year and cubic feet per m.g. | 20 |
| 5. Depth of sludge in tank each month | 10 |
| 6. Depth of scum in tank each month | 10 |
| 7. Settleable solids in influent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 2 |
| (*b*) Average during each month | 5 |
| (*c*) Maximum during each month | 2 |
| (*d*) Minimum during each month | 2 |
| 8. Settleable solids in effluent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 4 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| Total credits for perfect score | 100 |

## $G_1$. Primary Sedimentation (plain tanks—separate digestion).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of tanks, capacity and number of units | 10 |
| 2. Detention period based on present average sewage flow | 6 |
| 3. Frequency of sludge withdrawal to digester | 5 |
| 4. Frequency of skimmings removal | 4 |
| 5. Cubic feet of sludge removed during each month and cubic feet per m.g. | 25 |
| 6. Cubic feet of skimmings removed during each month and cubic feet per m.g. | 10 |
| 7. Settleable solids in influent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 3 |
| (*b*) Average during each month | 5 |
| (*c*) Maximum during each month | 3 |
| (*d*) Minimum during each month | 3 |
| 8. Settleable solids in effluent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 4 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 6 |
| (*d*) Minimum during each month | 6 |
| Total credits for perfect score | 100 |

## $G_2$. Primary Sedimentation (tanks with mechanical equipment).

(If used with Activated Sludge Plant, add appropriate information)

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of tanks, mechanical equipment, capacity and number of units | 10 |
| 2. Detention period based on present average sewage flow | 6 |
| 3. Frequency and average daily time sludge mechanism operated | 8 |
| 4. H.p. of scraper motor | 4 |
| 5. Frequency of sludge withdrawal to digester | 8 |
| 6. Cubic feet of sludge removed during each month and cubic feet per m.g. | 10 |
| 7. Frequency of skimmings removed | 6 |
| 8. Cubic feet of skimmings removed during each month and cubic feet per m.g. | 8 |
| 9. Settleable solids in influent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 3 |
| (*b*) Average during each month | 5 |
| (*c*) Maximum during each month | 3 |
| (*d*) Minimum during each month | 3 |

| *Item Reported Upon* | *Credits* |
|---|---|
| 10. Settleable solids in effluent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 4 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 6 |
| (*d*) Minimum during each month | 6 |
| Total credits for perfect score | 100 |

## $G_3$. Imhoff Tanks.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of tanks, capacities of sedimentation compartments and number of units | 5 |
| 2. Detention period based on present average sewage flow | 5 |
| 3. Total available sludge digestion capacity, 18″ below slot—cubic feet | 5 |
| 4. Frequency of sludge withdrawal | 3 |
| 5. Cubic feet of sludge removed during each month and cubic feet per m.g. annually | 12 |
| 6. Average quantity of sludge stored in tanks during each month (cubic feet) | 8 |
| 7. Depth of scum in gas vents each month | 3 |
| 8. Average pH of sludge in tank during each month | 5 |
| 9. Frequency of squeegeeing, skimming, hosing, etc. | 2 |
| 10. Cu. ft. of skimmings removed during each month and cu. ft. per m.g. | 4 |
| 11. Method of disposal of skimmings and gas vent scum | 3 |
| 12. Kind and amounts of chemicals used to aid digestion each month | 5 |
| 13. Settleable solids in influent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 3 |
| (*b*) Average during each month | 5 |
| (*c*) Maximum during each month | 3 |
| (*d*) Minimum during each month | 3 |
| 14. Settleable solids in effluent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 4 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 6 |
| (*d*) Minimum during each month | 6 |
| Total credits for perfect score | 100 |

## H. Chemical Precipitation.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Total lb. and lb. per m.g. of each chemical used during each month | 25 |
| 2. Feeding equipment, mixing device, flocculation devices, etc. | 10 |
| 3. Points of application of chemicals | 7 |
| 4. Rapidity of mixing; Detention in mixing stage | 10 |
| 5. Detention period for average sewage flow in flocculation stage—velocity of flocculators | 12 |
| 6. pH of influent before chemicals are added; max.—min.—average during each month | 12 |
| 7. pH of effluent—max.—min.—average during each month | 12 |
| 8. General comments relative to coagulation | 12 |
| Total credits for perfect score | 100 |

## I. Dosing Device(s).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type (single or twin, etc.) capacity, number of units, etc., etc. | 10 |
| 2. Number of siphons in each unit, alternating arrangements, drawing depth, etc. | 5 |
| 3. Average time required for dosing tank to fill | 10 |
| 4. Average time required for dosing tank to discharge | 10 |

| *Item Reported Upon* | *Credits* |
|---|---|
| 5. Average time between doses | 10 |
| 6. Frequency of cleaning | 5 |
| Total credits for perfect score | 50 |

## $J_1$. Trickling Filters.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type and number of units | 8 |
| 2. Total area and depth of filter | 8 |
| 3. Size and kind of filter medium | 8 |
| 4. Type of distributor, nozzles, etc | 8 |
| 5. Frequency and extent of nozzle and distributor cleaning | 10 |
| 6. Condition of bed with reference to pooling, growths, ice, flies, odors, etc., each month. | 10 |
| 7. Settleable solids in effluent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 4 |
| (*b*) Average during each month | 8 |
| (*c*) Maximum during each month | 6 |
| (*d*) Minimum during each month | 6 |
| 8. Relative stability of effluent. (This test not required if similar test is made of unchlorinated secondary tank effluent.) | |
| (*a*) Number of tests made during each month | 4 |
| (*b*) Average stability during month | 8 |
| (*c*) Maximum stability during month | 6 |
| (*d*) Minimum stability during month | 6 |
| Total credits for perfect score | 100 |

## $J_2$. Contact Beds.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Area, depth and number of beds | 14 |
| 2. Size and kind of filter medium | 8 |
| 3. Filling time (average) | 6 |
| 4. Contact time (average) | 6 |
| 5. Emptying time (average) | 6 |
| 6. Resting time (average) | 6 |
| 7. Settleable solids in effluent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 6 |
| (*d*) Minimum during each month | 6 |
| 8. Relative stability of effluent. (This test not required if similar test is made of unchlorinated secondary tank effluent.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average stability during each month | 10 |
| (*c*) Maximum stability during each month | 6 |
| (*d*) Minimum stability during each month | 6 |
| Total credits for perfect score | 100 |

## $K_1$. Secondary Sedimentation (plain tanks).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of tanks, capacity and number of units | 6 |
| 2. Detention period based on present average sewage flow, | 6 |

| *Item Reported Upon* | *Credits* |
|---|---|
| 3. Frequency of sludge withdrawal | 8 |
| 4. Cu. ft. of sludge removed each month and cu. ft. per m.g. | 16 |
| 5. Disposal of sludge | 10 |
| 6. Settleable solids in effluent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 6 |
| (*d*) Minimum during each month | 6 |
| 7. Relative stability of effluent. (Test not made if effluent has been chlorinated.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average stability during each month | 10 |
| (*c*) Maximum stability during each month | 6 |
| (*d*) Minimum stability during each month | 6 |
| Total credits for perfect score | 100 |

## $K_2$. Secondary Sedimentation (mechanical equipment).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of tanks, mechanical equipment, capacity and number of units | 8 |
| 2. Detention period based on present average sewage flow | 5 |
| 3. Frequency and average daily time sludge mechanism is operated | 6 |
| 4. H.p. of scraper motors | 5 |
| 5. Frequency of sludge withdrawal | 4 |
| 6. Cu. ft. of sludge removed during each month and cu. ft. per m.g. | 12 |
| 7. Disposal of sludge | 6 |
| 8. Settleable solids in effluent—ml. per liter (1 hour). | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 6 |
| (*d*) Minimum during each month | 6 |
| 9. Relative stability of effluent. (Test not made if effluent has been chlorinated.) | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 6 |
| (*d*) Minimum during each month | 6 |
| Total credits for perfect score | 100 |

## $K_3$. Secondary Clarifiers (Activated Sludge Plants).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of tanks, mechanical equipment, capacity and number of units | 8 |
| 2. Detention period based on present average sewage flow (without return sludge) | 6 |
| 3. H.p. of scraper motors | 2 |
| 4. Is speed of scrapers varied and if so, on what basis? | 4 |
| 5. To what point is excess activated sludge discharged? | 4 |
| 6. Suspended solids in effluent. | |
| (*a*) Number of tests made during each month | 4 |
| (*b*) Average during each month | 12 |
| (*c*) Maximum during each month | 6 |
| (*d*) Minimum during each month | 6 |
| 7. Turbidity in effluent. | |
| (*a*) Number of tests made during each month | 4 |
| (*b*) Average during each month | 8 |

| *Item Reported Upon* | *Credits* |
|---|---|
| (*c*) Maximum during each month | 4 |
| (*d*) Minimum during each month | 4 |
| 8. Relative stability of effluent. | |
| (*a*) Number of tests made during each month | 4 |
| (*b*) Average during each month | 12 |
| (*c*) Maximum during each month | 6 |
| (*d*) Minimum during each month | 6 |
| Total credits for perfect score | 100 |

## L. Intermittent Sand Filters.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type and number of units | 10 |
| 2. Total area and depth of filters; percentage of area in use at any time | 5 |
| 3. Kind and size of filter medium (effective size of uniformity coefficient of sand) | 5 |
| 4. Method and frequency of bed scraping, conditioning, cleaning, etc. | 10 |
| 5. Cubic feet sand removed annually | 8 |
| 6. Cubic feet sand replaced annually | 8 |
| 7. Million gallons of sewage applied per acre between rest periods | 10 |
| 8. Average period filter units are out of service for cleaning | 7 |
| 9. Condition of bed with reference to clogging, pooling, ice, etc., each month | 10 |
| 10. Relative stability or B.O.D. of effluent. | |
| (*a*) Number of tests made during each month | 5 |
| (*b*) Average stability during each month or average B.O.D. | 10 |
| (*c*) Maximum stability during each month or minimum B.O.D. | 6 |
| (*d*) Minimum stability during each month or maximum B.O.D. | 6 |
| Total credits for perfect score | 100 |

## M. Chlorination (Data for item 7 must be supplied to receive full credit when in judgment of Committee *B. coli* tests are regarded as essential).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of equipment and number of units | 10 |
| 2. Points of application of chlorine | 10 |
| 3. General purpose of chlorine treatment | 10 |
| 4. Lb. chlorine used each month and lb. per m.g. at each point of application | 20 |
| 5. Contact period for chlorine reaction | 5 |
| 6. Residual chlorine (p.p.m.). | |
| (*a*) Frequency of residual chlorine tests | 5 |
| (*b*) Average during each month | 14 |
| (*c*) Maximum during each month | 8 |
| (*d*) Minimum during each month | 8 |
| 7. Statement relative to method and frequency of making *B. coli* tests on final effluent | 10 |
| Total credits for perfect score | 100 |

## N. Aeration Tanks (activated sludge).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of tanks, and number of units; depth below flow line; width of channels and channels per tank; type and depth of diffusers | 4 |
| 2. Aeration period based upon present average sewage flow plus average percentage of returned sludge—by months | 2 |

| *Item Reported Upon* | *Credits* |
|---|---|
| 3. Air used per gallon of sewage flow for each month | 4 |
| 4. Power required for air compressors per m.g. of sewage—by months | 4 |
| 5. Power required for mechanical aerators per m.g. of sewage—by months | 4 |
| 6. Ratio of sludge returned to average sewage flow for each month | 4 |
| 7. Settleable solids in aeration tanks. Per cent by volume settling in 1/2 hour. | |
| (*a*) Frequency of tests | 2 |
| (*b*) Average during each month | 5 |
| (*c*) Maximum during each month | 3 |
| (*d*) Minimum during each month | 3 |
| 8. Suspended solids in aeration tanks—p.p.m. | |
| (*a*) Frequency of tests | 4 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| 9. Suspended solids in returned sludge—p.p.m. | |
| (*a*) Frequency of tests | 4 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| 10. Air pressure at compressor discharge or r.p.m. of mechanical aerators | 3 |
| 11. Excess sludge. | |
| (*a*) Total cu. ft. removed monthly, cu. ft. per m.g. annually and method of disposal | 5 |
| 12. Information of frequency and extent of sludge bulking | 4 |
| 13. Sludge index (Mohlman's—see THIS JOURNAL, 6, 21 (1934). Average and range during each month | 5 |
| Total credits for perfect score | 100 |

## O. SLUDGE CONCENTRATION DEVICES.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type, number of units, capacity and detention period | 20 |
| 2. Chemicals used in lb. per m.g. each month | 20 |
| 3. H.p. of motors and average hours used each day for each month | 10 |
| Total credits for perfect score | 50 |

## P. SLUDGE DIGESTION TANKS (list sludge storage tanks separately).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of digestion tanks, number of units, total capacity and appurtenances | 10 |
| 2. Digestion capacity actually used, based on average liquid level in tanks—for each month | 8 |
| 3. Average digestion temperature of sludge—for each month | 8 |
| 4. Average pH of sludge each month | 8 |
| 5. Kind and amounts of chemicals used to aid digestion—each month | 8 |
| 6. Average volume of heating water circulated daily—for each month | 4 |
| 7. Average temperature of water in heating boiler—for each month | 4 |
| 8. Average temperature of heating water to digester—for each month | 4 |
| 9. Average temperature of heating water from digester—for each month | 4 |
| 10. Cubic feet of sludge removed from digesters each month and cubic feet per m.g. annually | 20 |
| 11. Cubic feet of sludge in tanks each month | 8 |
| 12. Sludge liquor (supernatant)—method disposal | 4 |
| 13. Comments with reference to operating difficulties, scum, control, etc. | 10 |
| Total credits for perfect score | 100 |

## Q. Sludge Drying Beds.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of beds, number of units, depth sand and total area | 10 |
| 2. Average dept of dose of wet sludge on bed | 10 |
| 3. pH of sludge as applied to beds (give average for each month separately) | 10 |
| 4. Maximum, minimum and average drying time for sludge | 10 |
| 5. Amount and kind of chemicals used to condition sludge as applied to beds (for each month) | 10 |
| 6. Cu. ft. wet sludge applied during each month and how measured | 10 |
| 7. Cu. ft. air dried sludge removed during each month and cu. ft. per m.g. annually | 20 |
| 8. Disposal of sludge bed drainage | 10 |
| 9. Method of handling and disposal of dried sludge | 10 |
| Total credits for perfect score | 100 |

## R. Sludge Analyses—Omit if covered in Section III, Item G.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. State frequency of sampling and facilities for measurements and weighings | 10 |
| 2. Dry solids per cent in primary sludge (except Imhoff, plain and septic tanks)—for each month | 10 |
| 3. Dry solids per cent in sludge from concentration device—for each month | 10 |
| 4. Dry solids per cent in digested sludge to beds, lagoons or filters—for each month | 15 |
| 5. Dry solids per cent in dried sludge from beds or filters—for each month | 10 |
| 6. Average pounds (dry basis) of raw sludge solids per m.g. sewage treated for the year | 15 |
| 7. Average pounds (dry basis) of digested sludge solids per m.g. sewage treated for the year | 15 |
| 8. Average pounds per capita daily of raw solids recovered as sludge for the year (based on population tributary) | 15 |
| Total credits for perfect score | 100 |

## S. Vacuum Filters for Sludge Dewatering. (If centrifuge is used, report on appropriate items below.)

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of filter, dimensions, number of units and total filtering area | 10 |
| 2. Vacuum maintained on filter | 4 |
| 3. Number days filter operated in each month | 4 |
| 4. Number filter hours during each month (sum of all units) | 4 |
| 5. R.p.m. of filters (or centrifuge) | 4 |
| 6. H.p. of motors used during filtration | 4 |
| 7. Chemicals used for conditioning in lb. per 100 lb. of dry sewage solids—max.—min.—av. for each month | 10 |
| 8. Maximum and minimum and average pH of sludge before and after filtration for each month | 8 |
| 9. Average thickness of filter cake, inches | 4 |
| 10. Pounds of wet filter cake produced each month | 8 |
| 11. Per cent dry solids in filter cake—for each month | 8 |
| 12. Equivalent lb. of dry solids in cake each month and lb. per m.g. sewage flow | 12 |
| 13. Yield, dry sewage solids—lb. per sq. ft. per hr. | 10 |
| 14. Method of handling and disposal of cake | 4 |
| 15. Life of filter cloth—hours' use—month's service | 6 |
| Total credits for perfect score | 100 |

## T. Vacuum Filters for Treating Sewage or Effluent.

| *Items Reported Upon* | *Credits* |
|---|---|
| 1. Type of filter, dimensions, number of units, and total filtering area | 10 |
| 2. Number days filters operated during each month | 5 |
| 3. Number filter hours during month (sum of all units) | 5 |
| 4. H.p. of motors used during filtration | 5 |
| 5. Vacuum maintained on filter | 5 |
| 6. Chemicals or filter medium, pounds used each month and pounds per m.g. | 15 |
| 7. Average thickness of filter cake, inches | 5 |
| 8. Pounds of wet cake monthly and pounds per m.g. | 10 |
| 9. Dry solids per cent in filter cake—for each month | 10 |
| 10. Suspended solids in influent (p.p.m.), average monthly | 10 |
| 11. Suspended solids in effluent (p.p.m.), average monthly | 10 |
| 12. Method of handling and disposal of filter cake | 10 |
| Total credits for perfect score | 100 |

## U. Other Filtration Devices.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type, size, number of units—explain method of back-washing—disposal of wash water —loss of head, etc. | 30 |
| 2. Hours operated per day and total hours during each month | 20 |
| 3. Suspended solids or turbidity of influent—max.—min.—average—for each month | 20 |
| 4. Suspended solids or turbidity of effluent—max.—min.—average—for each month | 20 |
| 5. H.p. of motors used during filtration | 10 |
| Total credits for perfect score | 100 |

## V. Incineration (or Drying by Heat).

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type, number of units and rated capacity | 10 |
| 2. Temperature on each hearth (or at each point in process), max.—min.—average | 5 |
| 3. Preliminary drying or dewatering arrangements and results of treatment | 10 |
| 4. Amount and kind of auxiliary fuel used per ton of dry solids—for each month | 10 |
| 5. Tons of sludge cake or screenings fed each month | 15 |
| 6. Average dry solids and volatile content of sludge or screenings as fed | 10 |
| 7. Tons of dry sludge or screenings solids per m.g. of sewage flow—for each month | 10 |
| 8. Average daily time incinerator is in operation each month | 5 |
| 9. H.p. of motors used during operation of incinerator | 5 |
| 10. Average volatile content of incinerator ash | 5 |
| 11. Comments on operating difficulties | 10 |
| 12. Tons ashes per m.g.—for each month | 5 |
| Total credits for perfect score | 100 |

## W. Gas Collection.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Type of collector, gas-holder, appurtenances, etc. | 15 |
| 2. Cu. ft. of gas produced per day. | |
| (*a*) Average during each month and cu. ft. per capita | 10 |
| (*b*) Maximum during each month and cu. ft. per capita | 5 |
| (*c*) Minimum during each month and cu. ft. per capita | 5 |
| 3. Average $CO_2$ content of gas each month | 10 |
| 4. Gas pressure at meter | 5 |
| Total credits for perfect score | 50 |

## X. Gas Utilization.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. General uses made of gas | 10 |
| 2. Type of equipment, capacities, etc., for each unit utilizing gas | 15 |
| 3. Average daily cu. ft. of gas used in each unit for each month | 15 |
| 4. Statement regarding continuity of gas production and utilization—gas wasted—auxiliary fuel needed | 10 |
| Total credits for perfect score | 50 |

## Schedule III

*Analyses*

### A. Raw or Bar-screened Sewage Analyses (state which).

(To be submitted from all plants serving more than 10,000 and from all other plants where the necessary laboratory equipment is provided. For fine screening plants, omit B.O.D. of raw sewage)

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. General method of sampling and outline of procedure | 10 |
| 2. B.O.D. (5-day at 20° C.). | |
| (*a*) Number of tests made each month | 3 |
| (*b*) Average during each month | 9 |
| (*c*) Maximum during each month | 4 |
| (*d*) Minimum during each month | 4 |
| 3. Suspended solids. | |
| (*a*) Number of tests made each month | 3 |
| (*b*) Average during each month | 9 |
| (*c*) Maximum during each month | 4 |
| (*d*) Minimum during each month | 4 |
| Total credits for perfect score | 50 |

### B. Fine Screen Effluent.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. General method of sampling | 20 |
| 2. Suspended solids. | |
| (*a*) Number of tests made each month | 20 |
| (*b*) Average during each month | 30 |
| (*c*) Maximum during each month | 15 |
| (*d*) Minimum during each month | 15 |
| Total credit for perfect score | 100 |

### C. Primary Tank Effluent Analyses.

(To be submitted from all plants serving more than 10,000, from Activated Sludge and Chemical Precipitation plants, and from all other plants where the necessary laboratory equipment is provided)

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. General method of sampling | 16 |
| 2. B.O.D. (5-day at 20° C.). | |
| (*a*) Number of tests made each month | 8 |
| (*b*) Average during each month | 16 |

| *Item Reported Upon* | *Credits* |
|---|---|
| (*c*) Maximum during each month | 9 |
| (*d*) Minimum during each month | 9 |
| 3. Suspended solids. | |
| (*a*) Number of tests made each month | 8 |
| (*b*) Average during each month | 16 |
| (*c*) Maximum during each month | 9 |
| (*d*) Minimum during each month | 9 |
| Total credits for perfect score | 100 |

## D. Filtered Effluent Analyses.

(To be submitted from all plants serving more than 10,000, which have filters and from all other plants with filters where the necessary laboratory equipment is provided)

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. General method of sampling | 10 |
| 2. B.O.D. (5-day at 20° C.). | |
| (*a*) Number of tests made each month | 5 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| 3. Suspended solids (except for intermittent sand filters). | |
| (*a*) Number of tests made each month | 5 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| 4. Turbidity. | |
| (*a*) Number of tests made each month | 3 |
| (*b*) Average during each month | 6 |
| (*c*) Maximum during each month | 3 |
| (*d*) Minimum during each month | 3 |
| 5. Dissolved oxygen. | |
| (*a*) Number of tests made each month | 5 |
| (*b*) Average during each month | 10 |
| (*c*) Maximum during each month | 5 |
| (*d*) Minimum during each month | 5 |
| Total credits for perfect score | 100 |

## E. Final Tank Effluent Analyses.

(To be submitted from all plants serving more than 10,000 and from all other plants with final tanks, where the necessary laboratory equipment is provided)

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. General method of sampling | 10 |
| 2. B.O.D. (5-day at 20° C.). | |
| (*a*) Number of tests made each month | 4 |
| (*b*) Average during each month | 8 |
| (*c*) Maximum during each month | 4 |
| (*d*) Minimum during each month | 4 |

| *Item Reported Upon* | *Credits* |
|---|---|
| 3. Suspended solids (except for intermittent sand filters). | |
| (*a*) Number of tests made each month | 4 |
| (*b*) Average during each month | 8 |
| (*c*) Maximum during each month | 4 |
| (*d*) Minimum during each month | 4 |
| 4. Turbidity. | |
| (*a*) Number of tests made each month | 3 |
| (*b*) Average during each month | 6 |
| (*c*) Maximum during each month | 3 |
| (*d*) Minimum during each month | 3 |
| 5. Dissolved oxygen. | |
| (*a*) Number of tests made each month | 4 |
| (*b*) Average during each month | 8 |
| (*c*) Maximum during each month | 4 |
| (*d*) Minimum during each month | 4 |
| 6. Nitrates. | |
| (*a*) Number of tests made each month | 3 |
| (*b*) Average during each month | 6 |
| (*c*) Maximum during each month | 3 |
| (*d*) Minimum during each month | 3 |
| Total credits for perfect score | 100 |

## F. Analyses—Stream *Above* and *Below* Plant Outlet.

(To be submitted from all plants serving more than 10,000 and from all other plants where the necessary laboratory equipment is provided, and where such tests in judgment of Committee are significant)

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. General method of sampling | 20 |
| 2. Estimate of average monthly flow of stream and how obtained | 20 |
| 3. Average B.O.D. each month and number of tests | 20 |
| 4. Average D.O. each month and number of tests | 20 |
| 5. Average relative stability and number of tests | 20 |
| Total credits for perfect score | 100 |

## G. Sludge Analyses.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. State frequency of sampling and facilities for measurements and weighings | 10 |
| 2. Dry solids per cent in primary sludge (except Imhoff, plain and septic tanks)—for each month | 10 |
| 3. Dry solids per cent in concentrated sludge from concentration devices—for each month | 6 |
| 4. Dry solids per cent in digested sludge to beds, lagoons or filters—for each month | 10 |
| 5. Dry solids per cent in sludge from beds or filters—for each month | 10 |
| 6. Average pounds (dry basis) of raw sludge solids per m.g. sewage treated—for the year. | 10 |
| 7. Average pounds (dry basis) of digested sludge solids per m.g. sewage treated—for the year | 10 |
| 8. Average pounds per capital daily of raw solids recovered as sludge for the year (based on population tributary) | 10 |
| 9. Per cent fixed and volatile solids in raw sludge—for each month | 8 |
| 10. Per cent fixed and volatile solids in digested sludge—for each month | 8 |
| 11. Ether soluble matter in raw and digested sludge—for each month | 8 |
| Total credits for perfect score | 100 |

## Schedule IV

*Cost Data*

### A. Original Plant Cost.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Original cost of plant excluding intercepting sewers and pumping stations not located on plant site—and original cost per m.g. capacity | 25 |
| 2. Original cost of additions or modifications | 15 |
| 3. Present cost per m.g. capacity | 10 |
| Total credits for perfect score | 50 |

### B. Maintenance and Operation Costs for the Year.

| *Item Reported Upon* | *Credits* |
|---|---|
| 1. Salary of person in charge of plant proportioned in accordance with time devoted to plant operation and maintenance | 10 |
| 2. Total salaries of chemists, clerks or office personnel proportioned in accordance with time devoted to plant operation and maintenance | 10 |
| 3. Total wages of all other laborers and employees proportioned in accordance with time devoted to plant operation and maintenance | 10 |
| 4. Total power costs, itemized according to units, such as pumping, lights, etc. | 10 |
| 5. Total cost for chemicals, itemized according to chemicals used | 10 |
| 6. Total for miscellaneous or other costs. (Itemize if possible.) | 5 |
| 7. Grand total of all expenses during year for operation and maintenance | 10 |
| 8. Revenue from sale of sludge, etc. | 3 |
| 9. Credit for power sold | 3 |
| 10. Credit for gas delivered outside plant | 3 |
| 11. Total revenue | 6 |
| 12. Net total operating and maintenance expense for year (no. 7 less no. 11) | 10 |
| 13. Average cost per m.g. of sewage treated during year exclusive of amortization and interest | 10 |
| Total credits for perfect score | 100 |

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# EXCERPTS FROM ANNUAL REPORT OF SEWAGE DISPOSAL AND GARBAGE REDUCTION

## BOARD OF PUBLIC WORKS AND SANITATION

**City of Indianapolis, Indiana, 1938**

By D. E. Bloodgood, *Superintendent*

### Industrial Waste Survey

Continued efforts have been made to improve the efficiency of the catch basins of the many garages and filling stations throughout the city. It is with gratification that it can be said that the conditions have been improved. In most cases the owners and operators of the stations appreciate the necessity of the catch basins and co-operate very well in keeping them in good condition.

In the past, large quantities of paunch manure have been trouble-

some, but at the present time this can be kept to a minimum by rigid periodic inspections of the packing plants.

An effort has been made to keep up-to-date the record of the number of air conditioning units and the quantity of water discharged. The increase in the number of units was appreciable, but the quantity of waste water discharged to the sewers was not in proportion to the increase in new units. There were 186 systems in 1937 and 287 in 1938. The amount of water increased from 526,145 gallons per hour in 1937 to 617,437 gallons per hour in 1938.

### Grit Chambers

No trouble having been experienced with the discontinuance of the Speedway Grit Chamber, it was thought advisable to eliminate the Southern Avenue Grit Chamber. It is to be remembered that these two sewers pass through the West Indianapolis Grit Chamber before entering the plant. Some savings in electrical energy will be made by the above change.

It was necessary to make some changes in the mechanically operated grit chamber at West Street. The original installation called for almost continuous operation which was expensive because of the power consumed and the excessive wear on the moving parts. It is now possible to remove the grit at four hour intervals, under normal conditions, only a few minutes being required to remove the grit at each cleaning. The grit chambers have been shortened by at least half of their original length, thus cutting down on the length of the drags in the grit channels. This eliminates wear and is entirely satisfactory as far as grit removal is concerned. Washed grit is entirely satisfactory to use as fill for low ground.

### Clarification

Construction on two new primary tanks was started in October. They are similar in design to the older tanks except that the flights are used as grease skimmers on the new tanks. A grease skimming system for all units is being installed. The skimmings will be pumped to the digestion lagoons. Effluent weirs are to be placed in all of the primary tanks. It is expected that these will increase the efficiency of this part of the plant. A new sludge pumping building is being built and will house three Scru-Peller sludge pumps and a sludge meter.

The increase in sewage flow for the year is considerable. The reason for this is largely due to air conditioning water and excessive infiltration and run-off waters because of a rainfall of above average intensity. The per cent solids removal in the primary tanks is lower than usual, due in part to the low removal in December, when several of the units were out of service during the construction work, and a slight lowering of the solids in the raw sewage.

### Secondary Treatment

The increase in sewage volume over the year previous, taxed the secondary treatment plant to the maximum. In 1937 with an average

CLARIFICATION PLANT, SUMMARY OF OPERATION

| | Million Gallons per Day | Per Cent Treated Primary Tanks | Coarse Screenings Lb. per M.G. | Skimmings Lb. per M.G. | Grit Cu. Ft. per M.G. | Pri. Slg. Lb. Dry Sol. per M.G. | Per Cent Solids Removed in Clar. |
|---|---|---|---|---|---|---|---|
| Jan. | 49.53 | 47.7 | 13.10 | 15.87 | 3.29 | 793 | 27.3 |
| Feb. | 50.42 | 47.7 | 9.80 | 21.01 | 3.39 | 656 | 24.7 |
| Mar. | 50.80 | 49.4 | 7.25 | 22.55 | 4.35 | 830 | 28.8 |
| Apr. | 50.59 | 40.7 | 10.59 | 27.65 | 2.72 | 771 | 32.9 |
| May | 59.88 | 34.8 | 12.11 | 17.19 | 2.52 | 1081 | 38.7 |
| June | 57.75 | 37.0 | 9.97 | 17.80 | 3.25 | 815 | 48.9 |
| July | 63.28 | 36.0 | 6.64 | 9.41 | 3.12 | 648 | 30.7 |
| Aug. | 62.00 | 36.4 | 11.50 | 9.22 | 3.55 | 643 | 29.7 |
| Sept. | 51.63 | 44.7 | 11.20 | 17.69 | 3.09 | 790 | 29.8 |
| Oct. | 43.24 | 54.8 | 8.48 | 2.80 | 1.99 | 780 | 27.3 |
| Nov. | 50.60 | 49.0 | 9.20 | 2.70 | 2.60 | 852 | 29.1 |
| Dec. | 47.03 | 50.5 | 18.69 | 8.35 | 0.795 | 654 | 19.4 |
| Average | 53.07 | 43.5 | 10.66 | 14.34 | 2.93 | 779 | 29.2 |

PER CAPITA PER DAY FIGURES

| | |
|---|---|
| Gallons of Sewage | 128.18 |
| Suspended Solids, grams | 152.80 |
| B.O.D. Pounds (5 Day) | 0.213 |
| Grease, Grams | 37.20 |
| Cost Total Plant (Mills) | 1.209 |

Estimated 1938 Population 410,000 (Polk)

SECONDARY TREATMENT PLANT, SUMMARY OF OPERATION

*Activated Sludge Treatment*

| | Million Gallons per Day | Air Cu. Ft. per Gal. | Aeration Period Hours | Settling Gal. Sq. Ft. per Day Mixed Liquor | Lb. Solids Removed per M.G. |
|---|---|---|---|---|---|
| Jan. | 1.30 | 1.15 | 14.70 | 595 | 2301 |
| Feb. | 0 | —— | —— | —— | —— |
| Mar. | 0 | —— | —— | —— | —— |
| Apr. | 8.58 | 1.34 | 11.43 | 743 | ——* |
| May | 20.48 | 1.30 | 7.75 | 805 | 1469 |
| June | 38.26 | 1.13 | 7.40 | 875 | 1753 |
| July | 62.58 | 1.02 | 6.81 | 919 | 1462 |
| Aug. | 43.80 | 1.27 | 6.71 | 1165 | 1195 |
| Sept. | 39.40 | 1.37 | 7.02 | 1108 | 1650 |
| Oct. | 34.48 | 1.70 | 8.15 | 980 | 1980 |
| Nov. | 20.34 | 1.48 | 8.58 | 774 | 1587 |
| Dec. | 11.13 | 1.75 | 10.66 | 623 | 2479 |
| Yearly Total | 8408.40 (280 days) | | | | |
| Daily Average | 30.00 | 1.30 | 8.33 | 897 | 1801 |

* No sludge wasted while building mixed liquor solids.

0 No. 1 Plant down to replace air plates.

SECONDARY TREATMENT PLANT, SUMMARY OF OPERATION

*Plain Aeration of Sewage*

| | Million Gallons per Day | Air Cu. Ft. per Gal. | Aeration Period Hours | Settling Gal. per Sq. Ft. per Day | Lb. Solids Removed per M.G. |
|---|---|---|---|---|---|
| Jan. | 47.90 | 0.46 | 5.90 | 1477 | 1692 |
| Feb. | 49.76 | 0.45 | 5.64 | 1548 | 1681 |
| Mar. | 50.76 | 0.41 | 5.53 | 1579 | 1795 |
| Apr. | 47.32 | 0.54 | 5.92 | 1435 | 1539 |
| May | 38.96 | 0.60 | 7.20 | 1212 | 1712 |
| June | 28.50 | 0.68 | 9.85 | 1002 | 1527 |
| July | 00.00 | — | — | — | — |
| Aug. | 18.18 | 0.79 | 8.23 | 789 | 1337 |
| Sept. | 12.13 | 1.16 | 12.42 | 523 | 1770 |
| Oct. | 9.92 | 0.97 | 15.12 | 431 | 2086 |
| Nov. | 30.45 | 0.47 | 11.12 | 752 | 1804 |
| Dec. | 35.90 | 0.32 | 9.90 | 801 | 1616 |
| Yearly Total | 10,774.90 (321 days) | | | | |
| Daily Average | 33.57 | 0.53 | 7.83 | 1047 | 1698 |

CHEMICAL DATA

*Suspended Solids*

| | Raw Sewage P.p.m. | Rapid Settler Eff. P.p.m. | Clarified Eff. P.p.m. | Activated Sludge Eff. P.p.m. | Total Plant Eff. P.p.m. | Pri. Sludge | Plain Aeration Sludge | Return Sludge | Mixed Liquor | Resettled Act. Slg. to Pits |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan. | 333 | 181 | 246 | 12† | 49 | 4.13 | 4.85 | 1.07 | .31 | 3.33 |
| Feb. | 285 | 176 | 224 | — | 56 | 3.86 | 5.12 | — | — | — |
| Mar. | 331 | 187 | 234 | — | 52 | 4.99 | 6.44 | — | — | — |
| Apr. | 280 | 144 | 187 | 10* | 44 | 4.49 | 5.63 | 1.12* | .24* | — |
| May | 320 | 148 | 207 | 9 | 38 | 5.73 | 4.57 | 1.36 | .30 | 2.99 |
| June | 305 | 136 | 207 | 11 | 22 | 6.25 | 3.35 | 1.13 | .25 | 3.28 |
| July | 251 | 118 | 180 | 11 | 11 | 5.47 | — | 1.02 | .24 | 3.09 |
| Aug. | 267 | 122 | 188 | 17 | 22 | 5.19 | 2.53 | 0.97 | .28 | 2.63 |
| Sept. | 315 | 141 | 220 | 9 | 15 | 5.11 | 2.87 | 0.98 | .30 | 2.47 |
| Oct. | 345 | 151 | 251 | 8 | 18 | 4.89 | 2.94 | 0.96 | .30 | 2.40 |
| Nov. | 365 | 197 | 260 | 9 | 29 | 5.88 | 3.31 | 1.04 | .31 | 2.60 |
| Dec. | 416 | 258 | 324 | 10 | 35 | 3.93 | 4.18 | 0.97 | .34 | 1.68 |
| Average | 312 | 164 | 224 | 11 | 32 | 5.15 | 4.45 | 1.08 | .29 | 2.58 |

* 11 days only. † 24 days.

CHEMICAL DATA

*Nitrogen*

*Dry Basis*

| | Primary Sludge % | Plain Aeration Sludge % | Activated Sludge % |
|---|---|---|---|
| Jan. | 2.26 | 3.12 | 4.30 |
| Feb. | 2.38 | 2.95 | —— |
| Mar. | 2.03 | 2.51 | —— |
| Apr. | 2.48 | 3.20 | 4.67* |
| May | 2.60 | 3.53 | 4.50 |
| June | 2.42 | 3.51† | 4.13 |
| July | 2.55 | —— | 4.15 |
| Aug. | 2.68 | 3.79* | 4.72 |
| Sept. | 2.80 | 4.27 | 4.33 |
| Oct. | 2.78 | 4.02 | 4.91 |
| Nov. | 2.68 | 3.53 | 5.24 |
| Dec. | 2.69 | 3.23 | 4.99 |
| Average | 2.47 | 3.40 | 4.59 |

* 11 days. † 18 days.

CHEMICAL DATA

*5 Day Bio-Chemical Oxygen Demand, P.p.m.*

| | Raw‡ Sewage | Clarified Sewage | Plain Aeration Effluent | Activated Sludge Effluent | Effluent to River |
|---|---|---|---|---|---|
| Jan. | 249 | 241 | 90+ | 19* | 90 |
| Feb. | 253 | 231 | 116 | — | 116 |
| Mar. | 178 | 149 | 72 | — | 72 |
| Apr. | 184 | 158 | 72 | 26 | 85 |
| May | 243 | 201 | 86+ | 30 | 86 |
| June | 191 | 168 | 78† | 30 | 42 |
| July | 164 | 146 | — | 23 | 23 |
| Aug. | 217 | 196 | 57 | 27 | 36 |
| Sept. | 229 | 197 | 48 | 22 | 37 |
| Oct. | 280 | 251 | 69 | 19 | 38 |
| Nov. | 262 | 233 | 73 | 20 | 53 |
| Dec. | 321 | 291 | 97 | 15 | 64 |
| Average | 225 | 201 | 82 | 22 | 60 |

* 24 days; + Calculated = Total-Activated; † 20 days only; ‡ Calculated from B.O.D. of primary sludge and B.O.D. of clarified sewage.

CHLOROFORM SOLUBLE

*Dry Basis*

| | Primary Sludge % | Plain Aeration Sludge % | Activated Sludge % |
|---|---|---|---|
| Jan. | 22.2 | 31.9 | 9.4 |
| Feb. | 17.0 | 29.9 | — |
| Mar. | 13.4 | 23.4 | — |
| Apr. | 15.6 | 26.2 | 12.6* |
| May | 16.8 | 24.7 | 10.0 |
| June | 15.9 | 24.3† | 8.9 |
| July | 16.3 | — | 9.8 |
| Aug. | 17.2 | 25.4* | 9.6 |
| Sept. | 18.2 | 23.5 | 9.5 |
| Oct. | 20.2 | 26.5 | 9.6 |
| Nov. | 16.0 | 29.6 | 10.6 |
| Dec. | 19.8 | 32.4 | 11.7 |
| Average | 17.0 | 27.3 | 10.1 |

* 11 days.
† 18 days.
+ Acidified.

COST OF OPERATION PER M. G. OF SEWAGE TREATED

| | Grit Chamber and Interceptors | Clar. and Pumping | Secondary Treatment Plant | Sludge Disposal | Railroads and Lands | Total |
|---|---|---|---|---|---|---|
| Jan. | $1.54 | $5.20 | $4.24 | $0.67 | $0.30 | $11.95 |
| Feb. | 0.99 | 4.24 | 4.01 | 0.29 | 0.42 | 9.95 |
| Mar. | 0.92 | 3.33 | 3.31 | 0.17 | 0.44 | 8.17 |
| Apr. | 0.89 | 3.41 | 3.75 | 0.15 | 0.45 | 8.65 |
| May | 0.66 | 2.83 | 3.68 | 0.13 | 0.53 | 7.83 |
| June | 0.76 | 2.68 | 4.59 | 0.04 | 0.48 | 8.55 |
| July | 0.66 | 2.39 | 4.34 | 0.07 | 0.43 | 7.89 |
| Aug. | 0.81 | 2.86 | 4.74 | 0.09 | 0.40 | 8.90 |
| Sept. | 0.87 | 2.76 | 5.36 | 0.12 | 0.51 | 9.62 |
| Oct. | 1.01 | 3.42 | 7.49 | 0.16 | 0.36 | 12.44 |
| Nov. | 0.94 | 3.58 | 5.54 | 0.28 | 0.32 | 10.66 |
| Dec. | 0.89 | 3.56 | 4.33 | 0.36 | 0.35 | 9.49 |
| Average | $0.90 | $3.30 | $4.57 | $0.20 | $0.42 | $9.39 |

WHITE RIVER DATA

| | C.f.s. Flow* | Above Plant | | 6.25 Miles Below Plant | | 5 Day B.O.D. in Effluent Discharged to River Thousand Pounds Day |
|---|---|---|---|---|---|---|
| | | P.p.m. Dissolved Oxygen | Per Cent Saturation | P.p.m. Oxygen | Per Cent Saturation | |
| Jan. | 1013 | 12.4 | 89.5 | 10.6 | 78.7 | 36.4 |
| Feb. | 3550 | 12.1 | 93.0 | 10.8 | 82.3 | 48.0 |
| Mar. | 5282 | 11.0 | 90.3 | 10.7 | 87.6 | 29.4 |
| Apr. | 6935 | 8.8 | 89.6 | 8.2 | 83.2 | 31.0 |
| May | 1552 | 7.4 | 77.9 | 5.3 | 56.1 | 43.7 |
| June | 2897 | 6.6 | 75.0 | 5.7 | 64.9 | 19.6 |
| July | 1850 | 5.5 | 66.9 | 5.9 | 72.0 | 12.? |
| Aug. | 521 | 3.9 | 48.2 | 4.0 | 49.8 | 17.5 |
| Sept. | 344 | 3.5 | 40.8 | 3.9 | 47.5 | 15.8 |
| Oct. | 234 | 4.9 | 51.1 | 3.7 | 40.1 | 13.8 |
| Nov. | 317 | 7.6 | 68.7 | 5.1 | 48.7 | 22.0 |
| Dec. | 323 | 11.8 | 89.3 | 5.3 | 43.3 | 25.1 |
| Average | 2000 | 6.3 | 61.5 | 5.4 | 53.7 | 25.8 |

* Does not include sewage flow.

flow of 48.83 m.g.d., there were periods when an activated sludge became over aerated, while in 1938 with an average flow of 52.56 m.g.d. there were times when it was necessary to resort to plain aeration treatment of a small quantity of sewage even in the summer months. It should be mentioned here that plain aeration of sewage is practical during that part of the year when the more complete treatment is not necessary to keep the river in a satisfactory condition. The difference in cost of operation by the two methods, amounts to a saving of approximately $3,000 per month for coal.

## SLUDGE DISPOSAL

At the present time there is sufficient land available for building additional sludge pits as they are needed. At some future date, however, it will be necessary to take steps to provide a means of disposal of all digested sludge that cannot be used by market gardeners and farmers.

## RIVER DATA

The flow in White River was high on an average, especially during the first seven months. Though the per cent saturation below the plant was lower than the year previous, the condition of the river was satisfactory at all times. It should be noted that the river water during the critical months of July, August, and September, had less oxygen in it before the sewage plant effluent was discharged into it, than below the plant.

## Power Plant

The use of No. 5-1¼ in. washed screenings coal has improved operating difficulties in the power plant. It burns with less ash, which in times of heavy load is a great problem. The seriousness of a lack of an adequate supply of cool condensing water is still felt.

The K.W.H. produced during the year were 10.3 per cent higher than for 1937.

## Cost of Operation

The cost of operation of the sewage disposal plant per million gallons is slightly higher for 1938 than for 1937, but the 1.8 per cent increase in cost is much smaller than the per cent increase of labor cost, due to the increase in rate of salaries and wages and increase in personnel which amounted to 13.2 per cent.

# Editorial

## ACTIVATED SLUDGE RESEARCH IN THE LABORATORY

It is interesting to note the increase in the variety and scope of laboratory research on the activated sludge process, both in the United States and elsewhere. Activated sludge was discovered in the laboratory and in the early years of the development of the process laboratory research was indispensable to determine the properties and peculiarities of activated sludge. Later, as the engineering development progressed, more attention was paid to large scale testing station data and to operation data from full-scale plants. All such sources of information were eagerly investigated, and still are, because the rapid construction of large and costly plants made it imperative to study all possible economies in design, and therefore activated sludge research on a plant scale occupied the attention of most chemists and engineers interested in sewage treatment.

In the past five years, however, there has been renewed interest in the study of activated sludge in the laboratory. Although in the earlier years of research there seemed to be some doubt concerning the necessity for considering biological factors in the fundamental explanation of the mechanism of action of activated sludge, at the present time practically all investigators are convinced that physical chemical considerations alone are inadequate to account for the phenomena observed, and that bacteria and microorganisms play a necessary role in the transformations that occur. However, many of the laboratory investigations overlook the obvious fact that practical plant operation requires primary consideration of the control and adjustment of the circulating load of suspended solids, and that such control must be based on rates of flow, content of suspended solids, capacities of aeration and settling tanks, and settling rates of sludge. The B.O.D. of the sludge alone will not be sufficient to enable a plant operator to exercise much control over the process.

The laboratory research is essential, however, for a more satisfactory understanding of the way in which clarification is effected, the activity of the sludge, the rates of reactivation of sludge surfaces, the factors which affect oxygen requirements, and the nitrogen and carbon changes which occur during aeration. The laboratory and plant-scale researches may seem to follow apparently uncoördinated paths at present, but eventually the data accumulated in the laboratory will be utilized to make plant operation more efficient.

Laboratory work on activated sludge has been under way for a long time at the New Jersey Experiment Station, and a number of papers by Dr. Rudolfs and his co-workers have been published in THIS JOURNAL. The relation of solids concentration to degree of treatment, the mechanism of clarification, and the carbon and nitrogen transformations have been studied. Laboratory oxygen demand studies were reported by Grant, Hurwitz and Mohlman in 1930 and since then there has been considerable development in this type of research. The work of Kessler, Nichols and Sawyer has been of great interest. The present Journal contains their most recent contribution, dealing with the variation in oxygen utilization by several types of activated sludge, and the relation between organic content of sludge and oxygen utilization. Ruehhoft and his assistants at the U. S. Public Health Service Laboratory in Cincinnati have been reporting valuable results on the significance of the oxygen demand of sludge

as the most satisfactory test to determine its efficiency as a clarifying and oxidizing medium. Their present contribution in this issue is provocative, in that it indicates a lack of correlation between sludge index and oxygen demand, with the evidence pointing to the latter as the significant test for determining the activity and efficiency of activated sludge.

Bloodgood at Indianapolis also seems convinced that rates of oxygen demand are sufficient to serve as the primary test for plant control, and he has been operating the plant primarily on this basis, of course relying also on the physical tests of sludge concentration, sludge index, and dissolved oxygen content of the mixed liquor.

In England and Holland the oxygen demand of activated sludge has long engaged the attention of leading research chemists, and the laboratory work of Parsons and Wilson, Scouller and Goldthorpe, and Wooldridge and Standfast has been of value in showing the relations of sludge and oxygen in the activated sludge system. The laboratory work of the British Water Pollution Research Board has also been very stimulating in the attention it has paid to the various relations of carbon and nitrogen in activated sludge oxidation. Their most recent annual report for the year 1938 contains data on experiments cleverly contrived to show the significance of biological factors in nitrite reduction, the effect of temperature on rate of oxidation, and the coagulation of the colloids of sewage by activated sludge. The latter work leads them to the conclusion that "the main factor in the flocculation of organic matter in sewage by bubbles of gas is physical, though flocculation is influenced to some extent by biological action." Further work along these lines will be needed to correlate the laboratory work with plant operation.

The examples that have been cited of laboratory research on activated sludge are probably the outstanding ones, but work is also progressing along similar lines in plant laboratories and in university graduate schools. The latter field has not been developed widely, and offers interesting and valuable possibilities for extending our knowledge of activated sludge. We must, however, constantly consider the application of laboratory research data to the practical operation of plants, wherein so many variables must be controlled that do not appear to be important in the laboratory; and we must also guard against the danger of rationalization in interpreting the results of laboratory experiments. Certain abnormal factors may destroy the value of generalizations based on large amounts of data. Therefore laboratory research workers should be conservative and judicial in drawing conclusions from the results of their work.

F. W. M.

# Proceedings of Local Associations

## OKLAHOMA WATER AND SEWAGE CONFERENCE

**Fifteenth Annual Meeting**

**Stillwater, Oklahoma, January 19, 1939**

The fifteenth annual meeting was called to order at 7:00 P.M. by the Secretary, as both President and Vice-President were not in attendance.

Minutes of the previous meeting were read in full; motion made by C. L. Gibson, seconded by W. Stuart, carried.

Report of Secretary-Treasurer was read in full and a copy of same is attached and made a part of the minutes of the meeting. Motion was made by M. B. Cunningham, seconded by E. Stockton to accept report as read, carried.

The report of the committee consisting of E. M. Evans, F. D. Taaffe, E. R. Stapley, R. C. Dohe, H. M. LaRue and H. J. Darcey, appointed at the 1938 meeting to draft a program providing for a voluntary licensing program for the water and sewage plant operators and superintendents, was read. After some discussion the secretary was instructed to rewrite the sections in question, incorporating the suggested changes prior to submitting the proposed plan to a vote of the Conference.

The amended program, as follows, was read at length:

STATE DEPARTMENT OF PUBLIC HEALTH
State of Oklahoma

LICENSING PROGRAM

FOR

WATER AND SEWAGE PLANT SUPERINTENDENTS AND OPERATORS

*Examining Board:* Board to consist of five members to be selected as follows:

1. Representative of the Engineering School of the Oklahoma A. & M. College to be nominated by the Dean of the Engineering School, to serve for a period of four years.

2. Three members of the Oklahoma Water and Sewage Conference to be selected by the Executive Committee of the Conference and approved at the regular annual business session.

Vacancies to be filled by the Executive Committee, subject to the action of the membership at the regular annual meeting. The three members first appointed will serve terms of two, four and six years as determined by the Conference. Members appointed to succeed the original board shall all serve terms of six years.

The members of the Conference appointed to serve on this Board must be experienced in water and sewage plant operation and maintenance and shall at the time of appointment be employed as superintendents or operators.

3. The State Sanitary Engineer or a designated Assistant Engineer of the State Department of Public Health shall be a member of the Board and shall act as Secretary for the Board.

*Licenses:* Licenses will be issued for both water and sewage treatment plant superintendants and operators and will be issued for a specific type of plant. In case a holder of a license changes his position and assumes the responsibility of supervising or operating

a different type of plant, his license automatically becomes void and it will be necessary to apply to the Board for a new license. All licenses will be issued for a period of two years, and applicant will be subject to examination if deemed necessary by the Board before a license can be renewed.

*Associate Certificates:* Employees in the water and sewer departments who cannot qualify for a license but who have demonstrated their ability to perform the duties of their position under the direction and supervision of a licensed superintendent or operator, will be entitled to receive an Associate Certificate upon recommendation of his superior. These Certificates are subject to the same regulations and limitations as the licenses.

*Requirements for License:* Any person applying for a license must have two years' experience in plant operation, or he must be a registered professional engineer, or he must be a graduate of an accredited engineering school with six months' operating experience of a character approved by the Examining Board.

*Eligibles:* 1. Water or sewer system or plant superintendents. 2. Water or sewage plant operators directly responsible for the operation of the system or plant. 3. Laboratory directors only where they are in actual contact with the operation of water or sewage plants. Laborers around the plant, clerks and men employed as repair men on the distribution or collection systems will not be eligible for a license.

*Examinations:* Examinations will be held four times a year, or at the discretion of the Board of Examiners, but preferably in January, April, July and October. The examination will be given to all those whose applications meet the approval of the Board.

The applicants will not be required to assemble at any one place for the examination. The questions may be transmitted to the applicant by mail, and he will be permitted to use any available texts, notebooks or other technical data in answering the questions. The completed examination paper must be returned to the Secretary of the Board within one week from date received.

The Board of Examiners reserves the right to question any applicant and give further oral examination if it is deemed necessary to determine the qualifications of the applicant to hold such license.

At least three members of the Board must declare the applicant to have satisfactorily passed the examination before the applicant will be declared eligible for a license.

*Fees:* A fee of one dollar ($1.00) will be charged for each license or certificate issued, to defray the cost of printing, mailing and stenographic service.

Motion made by W. Stuart, seconded by Chas. Howard, to accept the proposed voluntary licensing program, carried.

Motion was made by Cecil Harrison, seconded by Wm. Belger, that the Conference approve the recommendations of the Board of Directors, naming M. B. Cunningham for the six year term, Chas. Howard for the four year term, and Leon Bennett for the two year term as representatives of the Conference on the Examining Board; motion carried.

The nominating committee consisting of Leon Bennett, Ancel Love and V. E. Stockton, submitted the following nominations for the officers of the Conference:

Earl Benedict, Hobart, *President,*
Elmer Edge, Shawnee, *Vice-President,*
H. J. Darcey, Oklahoma City, *Secretary-Treasurer.*

*Board of Directors*

L. H. Scott, Oklahoma City, Walter Bennett, Barnsdall,
Robert Kyle, Ardmore, Tom Brittain, Chickasha,
C. P. Peck, Stillwater, C. Abrams, Cleveland,
P. O. Williams, Clinton.

Motion was made by M. B. Cunningham that nominations cease and that all the nominees be elected by acclamation; motion seconded by Wm. Belger.

The Chairman of the Resolutions Committee, Mr. Cecil Harrison, Enid, submitted the report of the committee. Motion made by P. O. Williams to adopt the report as read, seconded by T. Brittain, carried.

Motion to adjourn.

H. J. DARCY, *Secretary*

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## SEWAGE DIVISION, TEXAS SECTION, S. W. W. A.

**Twenty-first Annual Meeting**

**College Station, Texas, February 13–17, 1939**

The Twenty-first Annual Texas Water Works and Sewage Short School met at College Station, February 13–17. The registration at this year's School set an all-time record with 285 men in attendance representing various groups and interests. Special out-of-state guests of the School included: H. J. Darcey, State Sanitary Engineer, Oklahoma City, Oklahoma; Dr. H. E. Goresline, U. S. Department of Agriculture, Washington, D. C.; Prof. Jack J. Hinman, Jr., Iowa State University, Iowa City Iowa; W. A. Reiman, Acting State Sanitary Engineer, Little Rock, Arkansas; J. H. O'Neill, State Sanitary Engineer, New Orleans, Louisiana; F. E. McDonald, Assistant State Sanitary Engineer, New Orleans, Louisiana; H. R. Murdock, Director of Research, Champion Paper and Fiber Company, Ashville, North Carolina; and C. J. Wilhelm, U. S. Bureau of Mines, Bartlesville, Oklahoma.

The program was divided into three sections: Water, laboratory and sewage. Prof. Hinman was invited to conduct the laboratory section which included demonstrations on discussions of special tests for water and sewage. Much interest was manifested by the attendants in all of the sessions where lectures were given on various phases of water and sewage plant operation and allied subjects. Special sessions were held in the evening in the form of round-table discussions on questions presented by the operators themselves.

A new feature of the School this year was a gadget session on Tuesday evening. All of the operators who had either, through necessity or interest, designed some sort of inexpensive "gadget" to do the work of more expensive equipment, were invited to bring such gadgets to the session for display and explanation.

The practice which was begun last year was continued at this School and on Wednesday evening there was a joint meeting of all of the district water and sewage associations in the State. There are now twelve such organizations in Texas of which eleven are active. Every group was well represented at this meeting where subjects of special interest to these organization such as programs, memberships, etc. were dis-

cussed. Mr. George J. Rohan, Superintendent of the Waco City Water Department, addressed the group on "Planning a Long Range Program" and gave some very helpful and interesting information.

Thursday evening the annual banquet was held in the College Mess Hall with Mr. J. L. Horner, President, presiding. Dr. George W. Cox, State Health Officer of Texas, addressed the group on the progress that has been made during the past year in the water and sewage fields including licensing of water and sewage plant operators, studies on stream pollution, cooperation with the State Vocational Education Department on training of water and sewage plant operators, etc. Prof. Hinman entertained the group with a well prepared and humorous lecture illustrated with slides and relating to Success. Five special awards were presented during the evening as follows: Dr. W. T. Gooch, Chairman of the Water Works Operators Licensing Committee, and Mr. E. J. M. Berg, Chairman of the Committee on Certification of Sewage Plant Operators, were each presented with Honorary Life Memberships in the Association in appreciation of the services rendered. The Rio Grande Valley Water and Sanitation Association was awarded a plaque for the greatest number of man-miles travelled by their members to attend the School. Dr. Cox on behalf of the Texas State Department of Health presented to Major Shawn of Randolph Field, a trophy in recognition of their having a sewage treatment plant which had produced the best effluent in the State for the year 1938. Another award was presented to Mr. Lewis A. Quigley of Fort Worth for displaying the most practical and unique gadget at the School.

Mr. V. M. Ehlers, Secretary, gave a report of the accomplishments of the School during the past year including the progress of the Manual for Water Works Operators which was published by this Association. Special reports from the following committees were read and accepted:

Resolutions Committee—Ashley G. Classen, El Paso, *Chairman.*
Auditing Committee—D. B. Dickson, Wichita Falls, *Chairman.*
Nominating Committee—Lewis A. Quigley, Fort Worth, *Chairman.*
Committee on Licensing of Water Plant Operators—Dr. W. T. Gooch, Waco, *Chairman.*
Committee on Certification of Sewage Plant Operators—E. J. N. Berg, San Antonio, *Chairman.*

New officers elected to serve for the ensuing year are: *President,* Ashley G. Classen, El Paso, *First Vice-President,* D. B. Dickson, Wichita Falls, *Second Vice-President,* S. C. Clark, San Benito, *Third Vice-President,* M. J. Salman, Commerce, *Fourth Vice-President,* Roy Matthews, Albany, *Trustee,* A. M. Brenneke, Denison, *Secretary,* V. M. Ehlers, Austin, *Assistant Secretary-Treasurer,* Mrs. Earl H. Goodwin, Austin.

V. M. Ehlers, *Secretary*

## KANSAS WATER AND SEWAGE WORKS ASSOCIATION

**Twelfth Annual Meeting**

**Lawrence, Kansas, March 16–18, 1939**

The twelfth annual meeting of the Kansas Water and Sewage Works Association was held at the University of Kansas, Lawrence, Kansas, on March 16–18, 1939.

The total registration was 145.

The preliminary laboratory school held on March 13–15 was attended by twenty operators.

The Association meeting opened on Thursday, March 16, at 9:30 A.M. with an address of welcome by Ivan C. Crawford, Dean of the Engineering School at the University.

H. L. Lingo, president, responded for the Association.

The secretary-treasurer's report was read and approved.

The morning papers were devoted to water treatment. Of the afternoon papers, one was on sewage treatment entitled, "The Combined Garbage and Sewage Disposal Plant at Winfield" by C. K. Mathews. Following this paper there was a panel discussion on "The Operation of Sewage Disposal Plants Using Sludge Gas for Power" by W. E. Baldry, R. B. Lee and P. L. Brockway.

In the evening the Association was invited to the annual banquet of the School of Engineering and Architecture.

Friday evening the annual banquet of the Association was held.

The papers on Saturday morning included: "Progress in Oil Field Waste Disposal in Kansas" by Ludwig Schmidt, and "Stream Pollution Control" by C. W. Klassen.

A round table on stream pollution was held following this last paper.

The newly elected officers of the Association are:

*President,* Robert Peart, Sterling.
*Vice-Presidents:* Levi B. Smith, Paola, F. W. Sieker, Yates Center, Wm. O'Day, Coffeyville, and Warren Johnson, Wichita.
*Secretary-Treasurer:* Earnest Boyce, Lawrence.

EARNEST BOYCE, *Secretary.*

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## NEW ENGLAND SEWAGE WORKS ASSOCIATION

**Tenth Anniversary Spring Meeting**

**West Springfield, Mass., May 15, 1939**

The tenth anniversary spring meeting of the New England Sewage Works Association was held on May 15, 1939, at the Springfield Country Club in West Springfield, Massachusetts. Eighty-seven members and guests were registered for the meeting. The morning session was called to order at 10:30 A.M. by President F. W. Gilcreas who presented

as the first speaker Mr. Robert Spurr Weston, Consulting Engineer, Boston, Massachusetts, who spoke on the subject of "Textile Waste Treatment." This was followed by a discussion by Professor Charles R. Hoover of Wesleyan University, Middletown, Connecticut.

The second paper of the technical session, "Status of Sewage Treatment in the Connecticut River Valley in Massachusetts," was presented by Mr. Clarence I Sterling, Jr., District Engineer, Massachusetts Department of Public Health, who described the proposed sewage treatment plants in the valley in the state of Massachusetts. Mr. Sterling outlined the work now under way.

The third paper of the morning session was presented by Mr. J. Henry L. Giles, Assistant Sanitary Engineer, Connecticut State Department of Health, on the subject of "Operation of Institutional Sewage Treatment Plants." This was discussed by Mr. Edward Sosnowski, operator of the Fairfield State Hospital sewage treatment plant at Newton, Conn.

There was some general discussion from the floor on all of the above papers. The morning session adjourned at 12:45 P.M.

The members met for luncheon in the main dining room of the Springfield Country Club at 1:00 P.M. After luncheon, the report of the Secretary was submitted and accepted by the membership. This was followed by a lively Question Box conducted by Mr. Morris M. Cohn of Schenectady, New York.

Following the Question Box, the members engaged in a putting contest for which prizes were awarded at dinner. Some members availed themselves of the opportunity for softball and golf.

The Association dinner was held at the Club at 6:00 P.M. Past Presidents Coburn, Lanphear, Scott, Brooks and Griffin were present. Past Presidents Bugbee, Fair and Gage were not in attendance. President Gilcreas gave a brief resumé of the first ten years.

The closing event of the day was a talk on aviation by the guest speaker, Mr. Charles L. Morris, Commissioner of Aeronautics for the State of Connecticut.

LeRoy W. Van Kleeck, *Secretary.*

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## CONFERENCE OF WISCONSIN SEWAGE WORKS OPERATORS

This is a new organization of which the first meeting was held on March 21–22, 1939, at Beaver Dam, Wisconsin.

It is believed that the Conference will fill a long felt need for a gathering in which the small town operators will feel free to express their opinions. The group is working toward the adoption of legislation requiring registration and examination of all sewage plant operators.

Fifty-seven were registered at the first meeting.

The organization is an outgrowth of the Sewage Works Operators Short Course. Its membership is limited to sewage plant operators and representatives of the sanitary engineering divisions of the State Board of Health and the various educational institutions of the State.

*Objectives:* Aside from the usual objectives such as the interchange of ideas and experiences etc., the Conference is working in conjunction with the Wisconsin Section of the A. W. W. A. and the State Board of Health for the adoption of legislation registering water works and sewage plant operators.

Inspection trip of the Beaver Dam Sewage Treatment Plant was made on the first morning. In the afternoon the following papers were presented: "Mechanical Drying of Sludge" by Paul Richter, "Sludge Digestion" by L. E. Langdon, "Sludge Disposal" by C. O. Baetz, "Gas Engine Operation and Gas Uses" by Carl Wahlstrom, and "Chemical Analysis" by J. Beatty.

After dinner in the evening, L. B. Penhallow gave a talk on lubrication.

The Wednesday session included papers by Jake Klein on "Paint Problems," "Pump Operation and Maintenance" by Burr Romaine, "Trickling Filters" by Oscar Ward, and "Plant Records and Costs" by George Martin.

*Officers for 1939*

Carl Walstrom, La Crosse, *President,*
O. E. Schwartz, Cedarburg, *First Vice-President,*
Willis Markisen, Union Grove, *Second Vice-President,*
W. J. Golueke, Green Bay, *Secretary-Treasurer.*

# Reviews and Abstracts

H. W. STREETER

## DISPOSAL OF AIR-DRIED SEWAGE SLUDGE AS A MANURE

BY J. W. FINCH, *Mgr. Rotherham Sewage Disposal Dept.*

*The Surveyor*, 95, 468–9 (1939)

During the period January to May, 1938, the Rotherham Sewage Disposal Department carried on an intensive campaign advertising the use of sewage sludge as a manure. This campaign was carried on because of accumulation of dried sludge at the Aldwarke Works. There had always been some demand for the sludge as manure, but in recent years its use declined because of the very high haulage rates charged by small contractors for odd loads, lack of knowledge of the properties of dried sewage sludge as a manure and its availability to the public, and prejudice against the use of sludge.

The department approached several haulage contractors and one of the largest agreed to haul 4-ton loads for from 8s. per load (if length of haul was under 2 miles) up to 10s. per load (for 3 to 4 mile hauls). Two-ton loads would be hauled for 4s. 6d. per load, under two miles, up to 5s. 6d. per load for 3 to 4 mile hauls. These lower rates were a decisive factor in the disposal of much more sludge for fertilizer purposes.

With regard to the second factor named above: All department lorries carried posters and signs advertising the sludge and haulage rates. The department issued three publications entitled:

"A Cheap and Excellent Form of Manure."
"The Technology of Soil Conditions Affecting Plant Growth."
"How to Use Sewage Sludge as a Manure."

Secretaries of 26 allotment associations were instructed in the value of sewage sludge as manure and one-hundredweight samples were distributed. Farmers were similarly approached.

As a result of all these efforts covering a 6-week period, orders came in at the rate of 100 tons per day and on the maximum day 151 tons were used. During the 5-month period January to May, 5,000 tons of sludge were disposed of as manure. Average age of the sludge used was 2 to 3 years. The information in this paper applies to the district of Rotherham with a population of 80,000, some 25,000 of these people living in surburban housing with gardens, and also to farms, market gardens and allotment societies within a radius of 5 miles from the source of supply of sludge. The sludge was sold for 2s. to 3s. per ton.

FRANK E. DEMARTINI

## NEUTRALIZATION OF ACID TRADE EFFLUENTS

BY J. MCNICHOLAS, *Asst. Sewage Works Mgr., Walsall*

*The Surveyor*, 95, 459–60 (1939)

A discussion of the problem is given followed by a description of the preliminary treatment plant recommended by the Walsall Corporation. The use of this acid neutralization plant is based on the plan of treating acid wastes at their sources.

The plant consists of a rectangular tank, with baffles at inlet and outlet, which serves as a chamber where the mixing and reaction of the acid waste with milk of lime can be

accomplished. Acid wastes enter the tank through an inlet feed channel with brick baffles. Milk of lime is added in this mixing and feed channel, 10 ft. ahead of the tank. Since most of the neutralization takes place in this channel it is stated that it is necessary to line only this feed channel with acid resisting materials, and not the whole tank. Tank capacity should be sufficient to allow thorough mixing and reaction with the lime. For waste volumes up to 10,000 gal. per day a tank capacity of 1,000 gal. is recommended. The milk of lime is kept in suspension in the lime feed tank either by manual stirring, compressed air or other mechanical means.

Principal types of acid wastes encountered were from cleaning or pickling of iron and steel (1% to 5% acid content and ferrous iron solution up to 8% by weight); a waste containing lead and nitric acid from a tube drawing works; effluent from a chromium plating works containing over 1,500 p.p.m. of chromium in terms of chromic acid; nickel plating wastes.

Reasons given for necessity of neutralization are:

1. Attack of sewers, both steel and concrete, and cement joints.
2. Reaction of acid wastes with sewage solids containing cyanides, sulfides, and sulfites resulting in production of poisonous gases.
3. Damage to mechanical plant—shafts, casings, pump impellers.
4. Odor nuisance at works due to liberation of odorous gases.
5. Growths in sedimentation tanks and tank effluent channels.
6. Sensitivity of purification processes to acid conditions and to metallic constituents of the wastes.

With respect to the metallic constituents it is stated that acid iron pickling wastes may be advantageous in aiding clarification. If not neutralized the flow of such wastes to the plant should be regulated by balancing tanks. In nickel plating wastes, the metal is completely precipitated upon neutralization. Cadmium plating wastes are not widely encountered. Neutralization of chromium plating wastes does not cause precipitation of the chromate group and soluble chromates are considered toxic to bacterial life, although not much is known concerning their exact influence on biological purification processes. Rather costly methods and skilled supervision would be required to eliminate the soluble chromates from acid chromium plating wastes. At Walsall removal of chromates has not been required since chromates have been found only rarely in the main outfall sewage.

FRANK E. DEMARTINI

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## THE PURIFICATION OF DAIRY WASTE WATERS

BY N. W. BARRITT

*Sewage Purification*, **1**, 118–122 (March, 1939)

"Milk wastes contain varying amounts of fat, protein and sugar—all of which are found in domestic sewage—and are readily decomposed by bacteria. The proportion of sugar to protein is much higher than in sewage but the fat is in varying degrees much less. A high sugar content in relation to nitrogen retards the purification, requiring a longer time of contact, and the addition of sewage or ammonia would be helpful, but this occurs only in the case of whey."

The trickling filter and the activated sludge processes are apparently the best possible methods of milk waste treatment. "Chemical precipitation methods are ruled out because there is no practical method of precipitating sugars and to remove the protein alone makes the sugars more difficult to purify than before."

*Biological Filtration (trickling filter).*—The trickling filter is a safe and reliable method under experienced management and produces good results under variable operating conditions when the contact time is satisfactory. This is due to the ability of the biological growths to adapt themselves to changing conditions within certain limits.

Filter materials should be carefully selected and graded with no material smaller

than 1½ in. mesh, and for maximum performance should be carefully placed. The wastes should have preliminary sedimentation to prevent clogging the filters. Septic tanks appear to be superior to other means of settlement for milk wastes. Several days detention is recommended but this depends upon temperature. Two tanks operated on the fill-and-draw principle at 24-hour intervals are considered superior to a single larger continuous flow tank. The wastes become acid during treatment but the pH does not exceed 4.0 even for the strongest whey. The use of lime is not considered necessary.

The B.O.D. of the milk washings is usually reduced by settling, for 24 hr., to about 450 to 900 p.p.m. (40%) which can be handled by an ordinary filter. Whey wastes undergo less reductions (about 20%), to a B.O.D. of around 1600 to 3600 p.p.m. which is too great for the ordinary filter at the usual rates of filtration.

Strong waste liquors may be reduced greatly by passage through lath or coarse gravel filters, which show removals of 45 per cent to 80 per cent B.O.D. before final filtration. Strong wastes may be diluted with domestic sewage before treatment to reduce load upon filters. Due to frequent observations that weak liquids require more filter medium for reduction of a given B.O.D. than do strong liquors, dilution is deceptive in its effects and may not be economic.

The most promising system for treating (*a*) milk and (*b*) whey washings by trickling filters is diagramatically as follows:

(*a*) Influent → Alternating Septic Tanks → Trickling filter → Effluent.
(*b*) Influent → Roughing filters → Settling tank → Trickling filter →Effluent.

*The Activated Sludge Process.*—This process is less elastic and shockproof than filtration. The sludge may be considered similar to a filter bed film in that it consists of similar microorganisms. Actually it differs in many particulars in that: (1) a considerable time is necessary to produce a good sludge; (2) there is no grading or zoning of organisms as the sludge is kept homogeneous by agitation; (3) rapid and complete settling is essential but this is impossible if the organisms have different settling rates. The sludge is limited to fewer types of organisms than are possible in a filter.

The most important limitation to the activated sludge process is the strength of the crude liquor, which is closely linked with the rate of aeration. At ordinary temperatures a B.O.D. of about 500 p.p.m. is the strongest that can be handled satisfactorily. At about 30° C. a liquid of 700 to 800 p.p.m. B.O.D. can be effectively purified in about 10 hr. aeration. Below 15° C. weaker liquors and longer aeration periods are required.

Against the limitations of the activated sludge process there is a great advantage in freedom from trouble due to suspended solids or readily flocculated substances in the crude liquors. The large Mogden installation can operate successfully without any preliminary sedimentation. The activated sludge process can be used for the treatment of milk washings if the B.O.D. is not too high, and no presettling tanks are necessary. Whey washings must be diluted or treated by preliminary roughing filters to reduce B.O.D. before aeration.

One plant used condenser water and domestic sewage to dilute the milk wastes and obtained a good effluent with B.O.D. reduction from 150 p.p.m. to 13 p.p.m., with an aeration rate of 3 cu. ft. per gallon. The sludge contained 17 per cent fat. The good results may be due in part to the use of hot condenser water as a diluent, which kept the temperatures nearer to the optimum. Temperatures in excess of 100° F. are detrimental and condenser water used as diluent should be controlled.

Another successful installation at Ellesmere produced a good effluent at temperatures of 10° to 15° C. with 20 per cent return sludge and a 24 hr. aeration period. With temperatures increased to 15° to 20° C. an effluent B.O.D. of 10 p.p.m. was maintained for over a year with influent B.O.D. of 350 to 500 p.p.m.

Experiments of the author at Rothamstead laboratory showed that no difficulty was encountered in treating milk and water, with 550 p.p.m. B.O.D., by the activated sludge process if the temperatures were kept above 15° C. At 30° C. effluents of less than 15 p.p.m. B.O.D. were obtained in 8 hr. aeration, and sludge of good settling characteristics was produced. Mixtures of 1 per cent milk with a B.O.D. of 1000 p.p.m. were reduced to less than 20 p.p.m. B.O.D. by aeration for 24 hr. at 30° C.

Kessener employed a surface aeration method for milk waste treatment in Belgium and France using 60 per cent return sludge and 3-day aeration periods. A similar plant used in the British Isles was not successful in treating milk wastes of 1500 p.p.m. B.O.D. with an aeration period of 30 hours.

The use of activated sludge as preliminary treatment to filtration is fundamentally wrong. Liquors too strong for trickling filters are too strong for the activated sludge process and are likely to lead to bad settlement of sludge and inefficiency.

"The problem of the purification of dairy waste waters is not one of lack of suitable methods, but rather of their correct understanding and application."

C. T. CARNAHAN

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## INDUSTRIAL WASTE TREATMENT PROCESSES AND PLANT DESIGN

BY E. F. ELDRIDGE

Michigan Engineering Experiment Station, *Bulletin* No. 82 (September, 1938)

Industrial wastes may be grouped into three general classes:

Organic wastes, from food or beverage productions or processing plants, tanneries, laundries, paper and straw-board mills, textile and dye works.

Toxic wastes, from metal plating or production plants, gas or chemical plants, coal or other mines.

Inert wastes, from water softening plants, oil wells, saw mills, gravel pits.

The method and degree of treatment of an industrial waste should depend upon the characteristics of the waste and the local requirements to eliminate or minimize objectionable conditions caused by the waste discharge.

The cost of treatment plants, in many cases, may be reduced by a segregation of the wastes requiring treatment from those which are relatively uncontaminated. Prior to the design of a plant, it will be necessary generally to determine the waste flow by weir measurements and the waste characteristics by analyses of samples composited according to the observed flow.

In the bulletin there are given treatment plant layouts, specific details for design of treatment units, and estimates of cost of treatment plant construction for several wastes which merit the close attenion of designers and others interested in waste treatment.

*Beet Sugar Factory Wastes:* Because of the differences in volume and characteristics, the various wastes from beet sugar factories are best treated separately.

Flume water, containing mostly tops, roots, and soil from washing, should require only fine screening, grit removal and sedimentation. Grit removal is most economically accomplished in conventional grit chambers, equipped with continuous removal equipment. Settling tanks should provide about 80 minutes detention at maximum flow and be provided with mechanical sludge removal equipment.

Process water (diffusion battery wash water and pulp press water) contains oxygen demanding materials, in solution or colloidal suspension, which may be coagulated by the application of 500 to 600 p.p.m. lime and then largely removed by sedimentation. The dosed waste should be coagulated for 20 to 30 minutes with slow stirring paddles and settled for about two hours in a mechanically equipped tank. In some cases, where the receiving body of water is small, further treatment, consisting of biological filtration, may be required.

Lime cake, where possible, should be discharged by belt conveyor or slurry pump. Where flushing with water is necessary, the material may be sluiced to large capacity ponds, or preferably, re-concentrated by settling and the resulting sludge dewatered on vacuum filters.

Steffens waste now is commonly disposed of by storage, and discharge during flood

periods. Treatment by evaporation seems promising for future development. It may be used for coagulation of process water, in proportions of about 1:24, in place of lime dosage. In some cases, adequate treatment and disposal may result by mixing, in factory proportions, the Steffens, process, and flume wastes, after removing grit from the latter; after coagulation with mechanical stirring for about 20 minutes and sedimentation for about 1.5 hours, the effluent will show a reduction of about 98 per cent of the suspended solids and 55 to 65 per cent of the 5-day B.O.D.

Two methods of disposal are available for the sludge produced by sedimentation of sugar beet wastes, *i.e.* ponding and vacuum filtration. Ponds must be of adequate capacity to hold the entire volume of sludge produced during the campaign without overflow. Vacuum filtration will reduce the sludge moisture content from about 85 to 45 or 50 per cent.

*Milk Products Factory Waste:* Milk wastes are composed, in general, of the washings and drainage from factory equipment. In the case of small plants, these wastes may be disposed of by application to several acres of cultivated land, odors being controlled by previous dosage with disinfecting agents.

Treatment of the wastes on standard or re-circulating type trickling filters, followed by sedimentation will effect 65 to 75 per cent reduction of B.O.D. The rate of filtration may be about 1 m.g.a.d. on a standard filter of 20 m.g.a.d. of the recirculating type when diluting the filter influent with 8 to 10 volumes of settling tank effluent. Small plants may find suitable a fill-and-draw process in which the entire day's waste is collected in a tank and applied over and over to the filter until the next day's waste must be received.

The Guggenheim process, with return activated chemical sludge, is capable of effecting 90 to 95 per cent reduction of B.O.D. A 4-hour aeration period should be provided, 30 p.p.m. of iron salt, 100 p.p.m. of lime, and 3 cu. ft. of air per gal. of waste being required.

*Metal Treating and Plating Wastes:* The treatment of pickling liquors should consist of neutralization and sedimentation, followed by aeration and settling out of the precipitated iron oxide. With small volumes, the fill-and-draw process can be employed to advantage. Two tanks should be provided, each capable of holding one day's waste discharge. The day's waste should be collected in the first tank, neutralized, and settled overnight. In the second tank, the settled liquor is aerated for most of the next day, allowed to settle and the clarified effluent is then discharged.

Plating room and other wastes containing cyanides should be treated to a high degree of removal by acidification and volatilization of the hydrocyanic acid. The process can best be used on batches. Sulfuric acid should be added gradually to the waste in a covered, vented tank, the liquor being aerated with compressed air. The amount of acid and aeration will depend upon the initial cyanide concentration; 16 hours aeration will usually suffice. Much care should be taken to dilute adequately the evolved gases before discharge, because of their toxic nature.

*Canning Factory Wastes:* For treatment of wastes from a "full-line" canner, where a large variety of products is manufactured, fine screening and biological filtration are required, plus chlorination in extreme cases where a very high degree of purification is desired. A rotary self-cleaning screen, with openings 0.01 to 0.12 inch size, is best suited for the purpose. The trickling filter design should allow an application rate of about 1 m.g.a.d. based on the maximum daily flow.

For treatment of wastes from specialized factories, biological processes are not readily adaptable; chemical precipitation is more suitable, at least for primary treatment. Following fine screening, the waste should be dosed with lime and ferric chloride, coagulated for at least 15 minutes with slow speed paddle mixing, and settled for at least 1.5 hours. The sludge produced will drain readily on underdrained sand beds.

At pea canneries, the concentrated waste stack juices from vine storage should be spread on land or, if this is not feasible, pre-treated with heavy lime application and sedimentation prior to treatment in combination with the other factory wastes.

*Meat Packing Plant Wastes:* For small packing plants, waste treatment by coagulation with chlorine followed by sedimentation is more positive of results than bi-

ological processes. With small waste volumes, utilization of a combination flocculation-sedimentation tank is most effective. After collection of the day's waste, chlorine gas should be introduced near the tank bottom until a rapidly settling floc is produced; further coagulation by ferric chloride dosage should then be produced. For average waste, about 4 lb. of chlorine and ⅛ gal. of 40 per cent ferric chloride solution will be required per 1000 gallons treated. The tank contents should be slowly stirred during chlorine and ferric chloride dosage and for about 15 minutes thereafter. After settling overnight, the clarified waste may be discharged. The sludge may be applied to land or dried on underdrained sand beds.

*Tannery Wastes:* Tanneries produce two major wastes, extremely variable in character due to periodic vat dumping. Beam house wastes, highly alkaline and containing large amounts of suspended solids, are comprised of hide washings, salt soaks, lime soaks and spent lime solutions. Tan yard wastes, composed of spent tan liquors and tan washings, are slightly acid and contain considerable dissolved material.

Chemical precipitation treatment of the mixed wastes will remove about 80 per cent of the suspended solids and 45 to 50 per cent of the B.O.D. If the hair has not been previously removed in the tannery, the beam house waste should be fine screened. The wastes should then be mixed, dosed with lime and ferric chloride, coagulated with mechanical mixing, and settled for at least 2 hours in a mechanically equipped tank.

At some tanneries, approximately the same results may be obtained by segregating the concentrated wastes from vat dumpings and the more polluted washings, and treating this smaller volume by chemical precipitation. The concentrated wastes are best settled by the fill-and-draw process.

Settled tannery sludge may be disposed of by lagooning or drying on underdrained sand beds. The sludge will dry rapidly in good weather.

Where secondary treatment of tannery wastes is required, biological filtration is recommended. The waste may be applied to the filter at a maximum rate of 1.5 gal. per sq. ft. per hour. This secondary treatment will accomplish an overall removal of 70 to 75 per cent of the initial B.O.D.

*Textile Wastes:* Textile mill wastes may be classified in four general types:

1. Deterging or cleaning wastes from wool scouring, cotton kiering, silk degumming, flax retting.
2. Bleaching wastes.
3. Miscellaneous wastes from desizing, mercerizing, weighting, carbonizing.
4. Dye wastes from dyeing, printing, finishing.

It is usually more economical to treat the combined wastes than the specific wastes individually. In all cases, chemical precipitation processes are required, sometimes followed by biological oxidation, usually in the form of filtration.

If dye wastes are to be decolorized, this may be accomplished by adding to them the bleaching wastes, augmented by chlorine dosage as necessary. Certain dyes are not susceptible to this treatment.

If the wastes are extremely acid or alkaline, they should be neutralized prior to treatment. Due to the rapidly changing character of the wastes, it is necessary to control acid or lime dosage by hand.

Fill-and-draw settling tanks are adapted to use at small mills where the maximum hourly waste flow does not exceed 12,000 gallons. For these, it is recommended that at least two hopper-bottomed tanks be provided, each with capacity for 5 hours flow accumulation, and equipped with coagulating paddles. The tank influent should be dosed with lime and ferric salt.

For a continuous flow treatment plant, a flow equalizing tank should be provided. The waste should be dosed with lime and ferric salt, mechanically flocculated for 15 to 20 minutes, and settled for about 1.5 hours. Mechanical equipment should be provided for the removal of the sludge, which can be dried readily on sand beds.

*Laundry Wastes:* At the sewage treatment plants of small communities and especially institutions, laundry wastes may cause operating difficulties due to excessive scum formation. Such difficulties may be eliminated by providing effective scum removal equipment or by separate treatment of the waste.

For separate treatment of this waste, both chemical precipitation and biological filtration have been used, the latter appearing to be preferable. In order to obtain more uniform dosage on the filter, a flow equalizing tank should be provided. The filtration rate should be about 1 m.g.a.d. over the daily flow period. Secondary sedimentation for about 2 hours is essential for efficient treatment, especially when treating a strong waste.

*Pulp and Paper Mill Wastes:* In the processes of manufacture of pulp and paper stock from wood, rags, or waste paper, chemicals are commonly used for removal of impurities and for bleaching. The wastes resulting are troublesome, especially those from the sulfite process of wood pulp manufacture. In addition to the chemical wastes, the processes for production of wood pulp, paper stock, and paper result in losses of varying amounts of fiber, the principal constituent in these "white-water" wastes. Prior to treatment, the chemical wastes should be segregated from the white water.

Treatment processes for the chemical wastes from pulp and paper stock mills have not been developed to the point where definite recommendations may be made. For sulfite liquor treatment, the Howard recovery process, consisting of stage treatment with lime to recover calcium sulfite and remove organic materials, seems promising and results in about 75 per cent reduction in the oxygen demand.

Dye wastes, in some cases, may be decolorized with chlorine or waste bleach liquor. Chlorine in waste bleach liquors may be largely removed by aeration. Sodium carbonate liquor from de-inking of reclaimed paper may be treated with calcium chloride and settled to remove suspended and precipitated solids.

For white water wastes, it is best to combine recovery of fiber with treatment. Fiber recovery may be accomplished by "save-alls" of the screen, vacuum filter, or settling tank type. The screen type is the least efficient and usually consists of a rotary drum screen with fine wire mesh cover, from which the fibers are mechanically removed. Vacuum filters, highly efficient in fiber recovery where the wastes contain little or no clay, are often used in connection with partial re-use of the water. Sedimentation save-alls are best adapted to wastes containing considerable clay; several hours detention in a mechanically equipped settling tank or 45 minutes detention in a multiple tray clarifier should be provided. Less efficient settling may be used if waste treatment is to follow the recovery process.

Treatment of white water following fiber recovery is best accomplished by chemical coagulation and settling. Following dosage with lime and ferric chloride, the waste should be mechanically coagulated for about 20 minutes and settled for about 2 hours, based on maximum hourly flow. Chemical dosages of about 100 p.p.m. lime and 25–50 p.p.m. ferric chloride will usually result in proper clarification. Mechanical equipment should be provided to remove the sludge, which will not dry readily and should be lagooned.

*Effect of Industrial Wastes on Municipal Sewage:* Municipal sewer systems are often called upon to handle industrial wastes which, in some cases, cause trouble by deterioration of the sewers or by interfering with proper treatment due to waste characteristics, volume, or strength.

Certain wastes should generally be excluded from the municipal sewage disposal system unless they are present only in very great dilution. These are: lime cake or Steffens waste from beet sugar factories, acid pickling liquors unless neutralized prior to discharge from the factory, plating wastes containing cyanides or copper salts, textile mill wastes, chemical wastes from paper pulp mills.

Some wastes may be treated in conjunction with the municipal sewage with general success, if the plant treatment units are properly and specifically designed for the extra loading. These are: flume water and process water from beet sugar factories, milk wastes, screened cannery wastes, packing house wastes, and tannery wastes. When the wastes constitute a large percentage of the total load on the municipal plant, separate treatment will usually be more effective and economical.

V. G. MacKenzie

## DESIGN, CONSTRUCTION AND OPERATION OF THE MELBOURNE SEWERAGE SYSTEM

By E. F. Bovrie

*Journal, Institution of Engineers, Australia,* 10, 351–365 (1938)

The Metropolitan Area of Melbourne contains 438 square miles, including 26 municipalities and parts of 12 others. The Melbourne and Metropolitan Board of Works is responsible for the water supply, sewerage and storm drainage. The climate is temperate, with an annual rainfall averaging from 17.34 to 25.65 inches, according to the location. The area is sewered on the separate system. Sewerage facilities are provided for 98 square miles, 261,782 premises, and 1,039,600 population—about 95 per cent of the total.

Most of the sewage is pumped and becomes stale, so that corrosion has developed in the rising mains and on ladders in manholes. The ladders are removed occasionally, heated and cleaned with a wire brush, and dipped in a priming bath of hot tar, followed by hot pitch enamel (75 per cent coal tar pitch; 25 per cent Trinidad asphalt; melting point 65 to 75 deg. C.). The rising mains have been reconditioned with a special pitch enamel, sprayed on. Grease balls are removed in amount some 161 tons annually. The sewage is collected by interceptors to a common point and discharged through a 15-mile outfall to the sewage farm. The details of the sewers and construction methods employed are described.

Manhole covers and frames are reseated by a special tool. Infiltration is held down, as well as storm runoff. From 2.34 to 4.21 per cent of the total precipitation actually was pumped at the main station.

The sewage is disposed of by irrigation on a farm, including 22,634 acres, well isolated. The treatment produces an effluent containing less than 20 p.p.m. 5-day B.O.D. and 30 p.p.m. suspended solids. Three methods of treatment are employed, land filtration, grass filtration and natural purification in lagoons. In the land filtration, a grass pasture (around 9,425 acres) is established, which is irrigated at a rate of one million Imp. gallons per day. Cattle, sheep and horses graze thereon, 3 to 5 days after watering, but the cattle are not used for human consumption. Grass filtration is handled in special bays 33 ft. wide and over 1,200 ft. long, in which there is a heavy growth of grass. After one year, a rate of loading is reached, not exceeding one million Imp. gallons per 20 acres per day. Up to date, pre-sedimentation has not been needed.

The annual average flow to the farm was 48.3 Imp. m.g.d., with an average dry weather flow of 46.5 m.g.d. The approximate age of the sewage was 16 hours.

Langdon Pearse

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## CITY OF JOHANNESBURG

### Annual Report of the City Engineer, Year Ending June 30, 1938

86 pp. + diagrams

This is a report issued by E. J. Hamlin, City Engineer, describing his work which includes streets, water supplies, sewers, sewage treatment, tramways, foundry and public cleansing (collection and disposal of household refuse).

Five sewage treatment works are operated, handling the sewage of 235,000 out of 271,800 Europeans and 105,000 out of 237,000 non-Europeans. A revenue is produced of £10,939. The total daily average flow was 10,210,000 Imp. gal., the smallest plant (Antea) handling 255,000 and the largest (Klipspruit) 6,552,000 Imp. gallons.

At Klipspruit the sewage is settled and distributed over land largely used for grazing, producing a revenue of £9,773 from all sources. This plant is being enlarged with separate digestion tanks and gas collection, and trickling fiter.

At the Antea works, yeast waste is now pumped over to the Klipspruit works.

At the Bruma works, new separate digestion works are nearly completed. The circular settling tanks are covered. Floating steel gas collectors are used.

At the Cydna works, new open sludge digestion tanks have been completed.

At the Delta works, an extension was put in service.

Research work on sewage treatment is carried on, particularly on trickling filters. A series of eight jacketed filters of 12-in. diameter were operated at various controlled temperatures to differentiate effects of temperature and ventilation. The effect of $CO_2$ was also studied on two 6-in. filters. High rate dosing was tested on a 3-ft. diameter filter. Tests on a plant scale are under way on ventilation.

Two articles are appended, viz.:

"Some Notes on the Ventilation of Percolating Filters," by E. J. Hamlin and H. Wilson.
"An Investigation into the Factors Affecting and Controlling the Drying of Sludge on Sludge-drying Beds," by B. L. L. Offell.

In the first article, following a historical review, the research work at Klipspruit on an enclosed Pruss filter is described. In the pilot plant, settled sewage is applied by a 4-arm revolving sprinkler to a filter 40 ft. internal diameter, with 5 ft. 7½ in. average depth of stone. The Pruss filter is identical except that it is covered and equipped with aerating tile. The preliminary results show that the enclosed filter was less sensitive to cold wind, and handled 3 to 4 times the output per cu. yd. of filter media than did the open filter.

The sewage is strong and fresh, containing from 195 to 383 p.p.m. oxygen absorved in 4 hr., ammoniacal N 66 to 122 p.p.m. and albuminoid ammonia from 12 to 40.8 p.p.m.

On the open filter, the Imp. gallons applied per cu. yd. varied from 33.8 to 62.6 after the first week. In the effluent, the nitrates varied from 0.3 to 35 p.p.m. The B.O.D. in the effluent ranged from 10.5 to 90 p.p.m. On the closed filter, the Imp. gallons applied per cu. yd. varied from 24.6 to 169.5. In the effluent, the nitrates varied from 0.0 to 22.8 p.p.m. The B.O.D. in the effluent ranged from 11.1 to 80.4 p.p.m.

In the second article, sludge bed design and operation are discussed, with the relation of evaporation and drainage. The water present was classified as free, capillary or combined. With well digested sludge (original moisture content around 95 per cent), about 60 per cent of the total volume of the sludge drains off as effluent. Practically all the effluent drains off in the first 18 hours, fairly uniformly. The drainage is negligible after 24 hours. About 20 per cent of the total volume is removed by evaporation in two weeks. The quantity of liquid lost by evaporation increases gradually throughout the experiments.

Under normal Johannesburg weather, a fairly well digested settled domestic sludge dries to spadeable condition in 10 to 12 days, when applied 8 to 10 inches deep. Such sludge is removable at 70 to 75 per cent moisture. Rain does not always hinder drying to the same extent. In general, 6-in. depth of application seemed best, although in very dry regions, as high as 18 inches might be applied.

A layer of sand from 4 to 6 inches deep was found most satisfactory. The efficiency of the sand apparently did not deteriorate in drainability with use. The important factors were found to be quality and type. A coarse sand with uniform size of particles is recommended, with very little fine material.

The type of treatment and nature of sludge may also affect the drying. A digested sludge gasifying freely dries rapidly and well.

LANGDON PEARSE

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